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Summary

Surface fatigue endurance tests were conducted with CVM AISI 9310 spur gears using a synthetic tetraester oil with oxidation and corrosion inhibitors and an antiwear additive as the lubricant. The lubricant conformed to MIL-L-23699 specifications. The tests were divided into four groups. In three of the groups either a 0.1 wt % sulfur- or phosphorus-type chemically reactive extreme-pressure (EP) additive was added to the base oil to enhance gear fatigue life. In the fourth group, the tetraester oil with only a standard additive package was used as a control.

The gear pitch diameter was 8.89 cm (3.5 in). Test conditions were a gear temperature of 344 K (160° F), a maximum Hertz stress of 1.71 GPa (248 000 psi), and a speed of 10 000 rpm, which gave a pitch-line velocity of 2800 m/min (9186 ft/min).

The gears tested with a 0.1 wt % phosphorus-type EP additive in the lubricant showed pitting fatigue life 2.6 times that of gears tested with the reference tetraester based oil. Although fatigue lives of the gears tested with a 0.1 wt % sulfur EP additive in the oil showed a slight improvement over gears tested with the reference oil, these results were not considered to be statistically significant.

Scanning Auger microscope (SAM) images made of the gear teeth after the tests showed that the gears tested with 0.1 wt % sulfur based and 0.1 wt % phosphorus based EP additives in the oil had sufficient amounts of FeS or PO₃ ions to enhance lubrication at the high gear tooth loads and the high sliding velocity generated during fatigue testing. This is important since estimates of the EHD lubricant film thickness at test conditions indicated that the gear teeth were operating in a marginal or boundary lubrication regime.

Introduction

Since gears are integral components in aircraft engine and transmission systems, the lubricant used must have a high load-carrying capacity in addition to the required viscosity at high-temperature conditions. To function adequately in this adverse environment, engine lubricants require an additive package in the base fluid that includes

oxidation and corrosion inhibitors, antiwear additives, a viscosity index improver, and, where gears are used, extreme-pressure (EP) additives. This is because, in most cases, an adequate fluid film cannot be maintained on the gear tooth surfaces. The type of EP additive required will depend on the severity of the conditions of the meshing gear teeth, such as sliding velocity, surface temperature, and contact load.

EP additives in the lubricant form a film on the gear surfaces that can increase significantly their load-carrying capacity. These films are formed by chemical reaction, adsorption, or chemisorption. Although these boundary films are 1 μm (40 μin) or less thick (ref. 1), they can provide separation of the metal surfaces when the elastohydrodynamic (EHD) film becomes thin enough for the asperities to interact. The boundary film probably provides lubrication by microasperity-elastohydrodynamic lubrication as the asperities deform under load. The boundary film prevents contact of the asperities and at the same time provides low shear strength properties that prevent shearing of the metal while reducing the friction coefficient below that of the base metal.

These films can provide lubrication at different temperature conditions, depending on the materials used. Some boundary films melt at a lower temperature than others and thus fail to protect the surfaces (ref. 2). The failure temperature is the temperature at which the lubricant film fails. In EP lubrication, the failure temperature is that at which the boundary film melts. The melting point or thermal stability of surface films appears to be one unifying physical property that governs the failure temperature for a wide range of materials (ref. 2).

Virtually all effective EP additives are organic compounds that contain one or more elements such as sulfur, chlorine, phosphorous, carboxyl, or carboxyl salt that can react chemically with the metal surface under conditions of boundary lubrication (ref. 3). When these compounds react with the metal surface they form inorganic films that can provide effective lubrication at high temperature and high sliding speed. These films are more stable than any physically or chemically adsorbed film (ref. 4). Elemental sulfur dissolved in oil has been used as a chemically reactive additive for many years. Moderately high concentrations of sulfur in oils exhibited the highest load-carrying capacity of any blend of oil subjected to EP lubrication. However, high wear rates

and the corrosive effects of sulphur in the oil and on metals are usually intolerable (ref. 4).

A synthetic base oil widely used in turbine engines because of its favorable high-temperature performance characteristics is a tetraester manufactured to the MIL-L-23699 specification. This lubricant, with the proper oxidation and corrosion inhibitors and antiwear additives, has been evaluated in a series of gear tooth scoring, load capacity, and fatigue pitting tests using both bench-type testers (refs. 5 to 8) and full-scale transmissions (ref. 8).

The objectives of this investigation were to (1) conduct surface fatigue life tests in the NASA spur gear fatigue test rig using a synthetic tetraester with and without EP additive packages, (2) compare the surface pitting fatigue lives of the test gears using the tetraester oil with and without the EP additives, and (3) determine, by means of Auger spectroscopy, the changes in chemical composition over the surface of the gear teeth and relate these changes to the effectiveness of the EP additives in formulation of the lubricant.

Four groups of consumable-electrode vacuum melted (CVM) AISI 9310 spur gears manufactured from the same heat of material were fatigue tested using a synthetic tetraester oil as the lubricant. Three groups of gears were tested with an EP additive package while a fourth group without EP additives acted as the control. Test conditions included a gear temperature of 344 K (160 ° F), a maximum Hertz stress of 1.71 GPa (248 000 psi), and a pitch-line velocity of 2800 m/min (9163 ft/min).

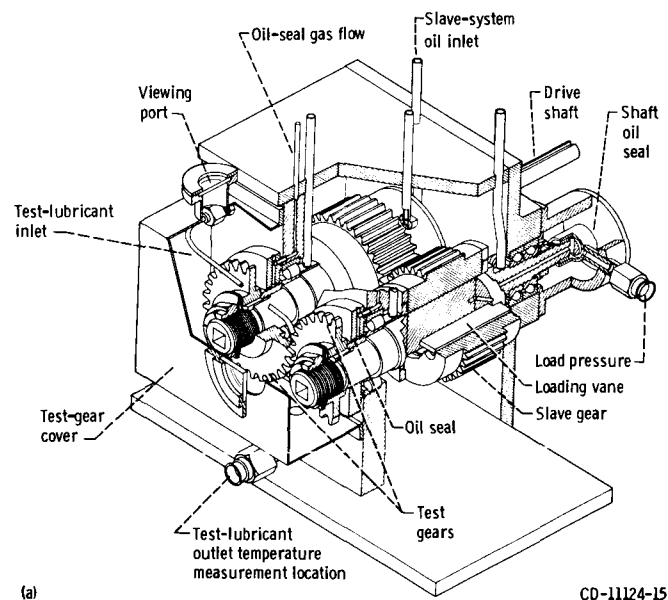
Apparatus, Specimens, and Procedure

Gear Test Apparatus

The gear fatigue tests were performed in the NASA Lewis Research Center gear test apparatus (fig. 1). This test rig uses the four-square principle of applying the test gear load so that the input drive need only overcome the frictional losses in the system.

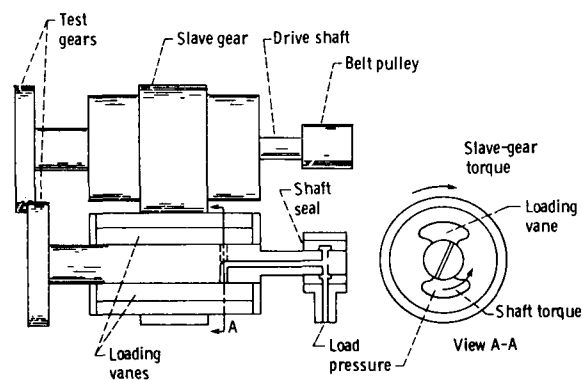
A schematic of the test rig is shown in figure 1(b). Oil pressure and leakage flow are supplied to the load vanes through a shaft seal. As the oil pressure is increased on the load vanes inside the slave gear, torque is applied to the shaft. This torque is transmitted through the test gears back to the slave gear, where an equal but opposite torque is maintained by the oil pressure. This torque on the test gears, which depends on the hydraulic pressure applied to the load vanes, loads the gear teeth to the desired stress level. The two identical test gears can be started under no load and then the load can be applied gradually without changing the running track on the gear teeth.

Separate lubrication systems are provided for the test gears and the main gearbox. The two lubricant systems



(a)

CD-11124-15



(b)

CD-11124-15

(a) Cutaway view.
(b) Schematic diagram.

Figure 1.—NASA Lewis Research Center's gear fatigue test apparatus.

are separated at the gearbox shafts by pressurized labyrinth seals. Nitrogen was the seal gas. The test gear lubricant is filtered through a 5- μ m nominal fiberglass filter to remove wear particles.

A vibration transducer mounted on the gearbox automatically shut off the test rig when gear-surface fatigue occurred. The gearbox also automatically shut off if a loss of oil flow to either the main gearbox or the test gears occurred, or if the test gear oil overheated, or if there was a loss of seal gas pressurization.

Test Gears

The gears were manufactured from a single heat of CVM AISI 9310 steel. The chemical composition of the AISI 9310 gears is given in table I. The heat treatment for

TABLE I.—CERTIFIED CHEMICAL COMPOSITION OF GEAR MATERIAL
CVM AISI 9310 AMS 6265D

	Element									
	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Fe
Contents, wt %	0.11	0.64	0.007	0.004	0.34	3.18	1.33	0.17	0.26	Balance

the AISI 9310 gears is given in table II. Photomicrographs of the etched and polished surface from the case and core regions of the gear are shown in figure 2. The case hardness of the gears was Rockwell C 61 to 63. The gear core hardness was Rockwell C 38 to 40.

Dimensions for the AISI 9310 test gears are given in table III. All gears have a nominal surface finish on the tooth face of $0.35 \mu\text{m}$ ($14 \mu\text{in}$) rms and a standard 20° involute profile with a tip relief of 0.001 to 0.0015 cm (0.0005 to 0.0007 in).

Test Lubricants

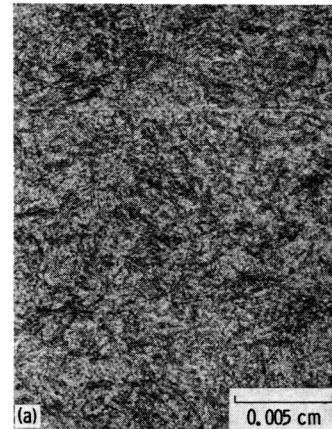
The gears in this fatigue pitting investigation were lubricated with a synthetic tetraester based oil (MIL-L-23699) containing oxidation and corrosion inhibitors plus a load-carrying additive. The lubricant was formulated in four batches (NASA I to IV) with each batch having the constituents shown in table IV. The physical properties of the lubricants are also summarized in table IV.

Lubricant was supplied to the inlet mesh of the test gears by jet lubrication. A total of 3800 cm^3 (1 gal) of lubricant was used for each test and then discarded, along with the filter element. Inlet and outlet oil temperatures were recorded continuously on a strip-chart recorder.

Lubricant was recirculated at a constant flow rate of $800 \text{ cm}^3/\text{min}$ (0.21 gal/min) to the gear mesh. The average lubricant inlet temperature was $322 \pm 6 \text{ K}$ ($120^\circ \pm 10^\circ \text{ F}$), and the lubricant outlet temperature averaged about $344 \pm 6 \text{ K}$ ($160^\circ \pm 10^\circ \text{ F}$). The outlet temperature was measured at the outlet of the test-gear cover.

TABLE II.—HEAT TREATMENT FOR AISI 9310

Step	Process	AISI 9310		
		Temperature		Time, hr
		K	$^\circ\text{F}$	
1	Carburize	1172	1650	8
2	Reheat	922	1200	2.5
3	Austenitize	1117	1550	2.5
4	Subzero cool	180	-120	3.5
5	Double temper	450	350	2 each
6	Stress relieve	450	350	2



(a) Carburized and hardened case of the CVM AISI 9310 gear showing high carbon fine grain martensitic structure.
(b) Core structure of CVM AISI 9310 gear showing low carbon refined austenitic grain size.

Figure 2.—Photomicrographs of case and core regions of test gears.

Test Procedure

The test gears were cleaned with a solvent to remove the preservative coating and then assembled on the test rig. The test gears were run in an offset position with a 3.1-mm (0.12-in) tooth-surface overlap to give a load width on the gear face of 2.8 mm (0.11 in) of the 6.4-mm-(0.25-in-) wide gear, thereby allowing for the edge radius of the gear teeth. Four fatigue tests could be run on each set of gears by testing both faces of the gears. All tests were run-in at a normal load of $2.714 \times 10^5 \text{ N/m}$ (1550 lb/in) for 1 hour. The normal load was then increased to $6.16 \times 10^5 \text{ N/m}$ (3518 lb/in) with a 1.71 GPa

(248 ksi) pitch-line Hertz stress. At the pitch-line load the tooth root bending stress was 0.226 GPa (32.7 ksi) if plain bending was assumed. However, because there was an offset load there was an additional stress imposed on the tooth bending stress. This did not cause edge loading since both teeth deflected the same amount at the pitch line. Combining the bending and torsional moments gave

a maximum root stress of 0.286 GPa (41.5 ksi). The test gears were operated at 10 000 rpm, which gave a pitch-line velocity of 2800 m/min (9186 ft/min). The tests were run continuously (24 hr/day). Shutdown was achieved automatically by a vibration-detection transducer located on the gearbox, adjacent to the test gears, when vibration amplitude exceeded a preset value.

TABLE III.—SPUR GEAR DATA

[Gear tolerance per ASMA class 13.]

Number of teeth.....	28
Diametral pitch.....	8
Circular pitch, cm (in).....	0.9975 (0.3927)
Whole depth, cm (in).....	0.762 d(0.300)
Addendum, cm (in).....	0.318 (0.125)
Chordal tooth thickness reference, cm (in).....	0.485 (0.191)
Pressure angle, deg.....	20
Pitch diameter, cm (in).....	8.890 (3.500)
Outside diameter, cm (in).....	9.525 (3.750)
Root fillet, cm (in).....	0.102 to 0.152 (0.04 to 0.06)
Measurement over pins, cm (in).....	9.603 to 9.630 (3.7807 to 3.7915)
Pin diameter, cm (in).....	0.549 (0.216)
Backlash reference, cm (in).....	0.0254 (0.010)
Tip relief, cm (in).....	0.001 to 0.0015 (0.0005 to 0.0007)

The pitch-line elastohydrodynamic (EHD) film thickness was calculated by the method of reference 9. It was assumed, for this film thickness calculation, that the gear temperature at the pitch line was equal to the outlet oil temperature and that the inlet oil temperature to the contact zone was equal to the gear temperature, even though the oil jet temperature was considerably lower. It is probable that the gear surface temperature could be even higher than the oil outlet temperature, especially at the end points of the sliding contact. The EHD film thickness for the tetraester reference oil was computed at 0.731 μm (28.8 μin) which gave a ratio of film thickness to composite surface roughness (h/σ) of 1.22 at the 1.71-GPa (248-ksi) pitch-line maximum Hertz stress. The EHD film thickness computed previously for the reference oil was the same as that for the lubricants with the additives contained therein. This is because small

TABLE IV.—LUBRICANT COMPOSITION AND PROPERTIES

(a) Compositions

	NASA lubricant			
	I ^a	II	III	IV
	Composition, wt %			
Tetraester base oil	95.4	95.3	95.3	99.4
Amine-type oxidation inhibitor	2.5	2.5	2.5	.5
Phosphate quinizain corrosion inhibitor plus metal passivator	2.1	2.1	2.1	
Alkyl amine thiocyanate EP additive		.1		.1
Alkyl acid phosphate EP additive			.1	
Water	.019	.020	.010	.016

(b) Properties

	NASA lubricant			
	I ^a	II	III	IV
Kinematic viscosity (CS) at—				
311 K (100° F)	27.58	27.90	27.90	26.40
373 K (212° F)	5.22	5.17	5.18	5.08
Flash point, K (° F)	527 (490)	533 (500)	527 (490)	533 (500)
Pour point, K (° F)	213 (-76)			
Specific gravity at—				
311 K (100° F)	0.982	0.982	0.982	0.979
373 K (212° F)	0.943	0.943	0.943	0.939
Total acid number (TAN), mg KOH/g oil	0.02	0.31	0.29	0.15

^aMeets MIL-L-213699 specifications.

concentrations of additives in an oil do not influence its viscosity or viscosity—pressure coefficient significantly (ref. 10).

Posttest Examination of Gear Tooth Surfaces

To determine whether the EP additives provided effective lubrication during the fatigue tests, the gear tooth surfaces were examined after testing with a scanning Auger microscope (SAM). This instrument identifies the elemental composition of the surface layers of a solid. A tooth was cut from each of the five gears (four of these gears had been run with the lubricants of table IV and one had not been used). Water was used to lubricate and cool the gear during the abrasive cutting of the teeth. The gear teeth were washed in acetone and 190 proof alcohol and then mounted in the SAM system. The system was baked to 433 K (320° F) and evacuated to a pressure of 1.33×10^{-8} N/m². The system was then backfilled with ultrapure argon to a pressure of 1.2×10^{-2} N/m².

The SAM instrument can be used in two modes, a spot mode and a SAM mode. In the spot mode the specimen surface is bombarded with electrons and the emitted secondary electrons are detected and their energy analyzed. The detector is a single-pass cylindrical mirror analyzer with a resolution of 1.2 percent when used in the derivative mode at a modulation of ± 4 eV. The probing electron beam is held in a fixed position on the specimen while the detector sweeps the energy spectrum of the emitted (secondary) electrons. This produces a spectrum in the form of energy (eV) as a function of intensity as shown in figure 3. Where an energy peak occurs, an element is identified as to its atomic species, and the peak amplitude (relative intensity) is a measure of its concentration. In the SAM mode the detector pass energy is set at a level corresponding to the element of interest and the electron beam is rastered to indicate the concentration of the element as a function of position. The system is equipped with an ion gun to sputter clean the surface of the sample. Spectra produced during this process can give a picture of the variation of the

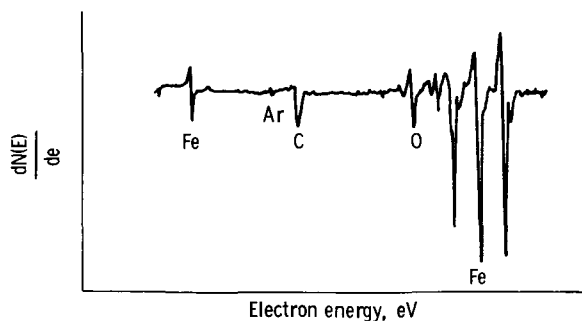


Figure 3.—Spectrum of electron energy as function of intensity for unrun CVM AISI 9310 gear showing iron (Fe), argon (Ar), carbon (C), and oxygen (O) peaks.

composition of the surface as a function of depth. The electron gun was operated at 2 kV at a current of $0.2 \mu\text{A}$ in the spot mode and at a current of $2 \mu\text{A}$ in the SAM mode. Typically, Auger spectra were taken in the spot mode and then imaged at energies corresponding to the elements of interest. The sample was then rotated so that it was approximately 45° to the axis of the ion gun and sputter etched with a 3-kV ion beam at a current density of $4 \times 10^3 \mu\text{A}/\text{cm}^2$. They were then rotated such that they again were perpendicular to the electron beam, and the spot and area analyses were repeated. This process was continued until an Auger spectrum independent of sputtering time was observed. This spectrum was in all cases identical with that of the unused gear, since all additive film had been removed.

Results and Discussion

Gear Endurance Tests

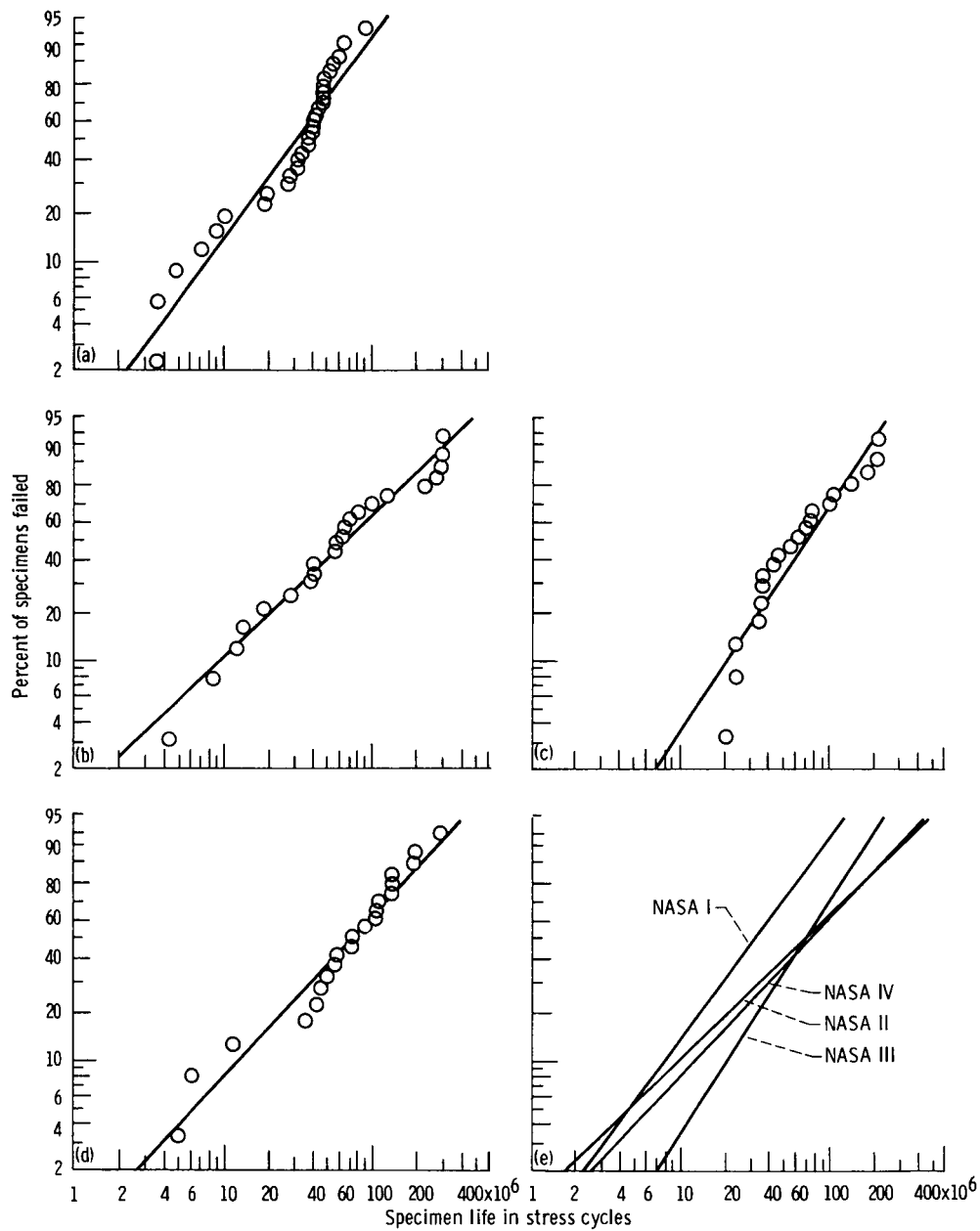
Four groups of CVM AISI 9310 gears from the same heat of material were fatigue tested in pairs until failure. Maximum Hertz stress was 1.71 GPa (248 psi). Each group was evaluated using a synthetic tetraester oil with one of the four additive packages described previously (table IV).

Surface fatigue results for the gears are shown in figure 4 and summarized in table V. The data were analyzed using the methods of Johnson (ref. 11). The surface (pitting) fatigue lives were 7.61×10^6 and 31.0×10^6 stress cycles for the 10- and 50-percent lives, respectively, for the gears tested with the NASA I (reference) oil containing oxidation and corrosion inhibitors. The failure index, the number of fatigue failures out of the number of sets tested, was 30 out of 30.

Fatigue lives for the gears tested with the NASA III (plus phosphorous oil) were 19.8×10^6 and 67.1×10^6 stress cycles for the 10- and 50-percent lives, respectively (fig. 4(c)). These tests indicated a 10-percent fatigue life, which is 2.6 times that of the gears tested with the reference oil. These results indicate a statistically significant improvement in gear fatigue life using the phosphorous oil. The confidence number for the difference in the 10-percent lives was 92 percent. Confidence numbers above 90 percent are considered to be statistically significant. The mean life ratio for the phosphorous oil over the reference oil was 2.16 (table V).

A comparison of the 10-percent gear fatigue lives between the NASA II (sulfur) oil and the reference oil (fig. 4(e) and table V) indicates that the 0.1 wt % sulfur EP additive has some beneficial effect, although the life improvement is not statistically significant.

The amount of oxidation and corrosion inhibitors used in the lubricant with the 0.1 wt % sulfur EP additive appears to effect gear fatigue life. The oil which had a 0.5



- (a) Tetraester (reference) oil with 2.5-percent oxidation inhibitor plus 2.1-percent corrosion inhibitor (NASA I).
- (b) Tetraester oil with 0.1 wt % alkyl amine thiocyanate (sulfur) EP additive (NASA II).
- (c) Tetraester oil with 0.1 wt % alkyl acid phosphate (phosphorous) EP additive (NASA III).
- (d) Tetraester oil with 0.1 wt % alkyl amine thiocyanate (sulfur) EP additive and without phosphate quinizain corrosion inhibitor/metal passivator (NASA IV).
- (e) Surface pitting fatigue life of CVM AISI 9310 spur gears. Pitch diameter, 8.39 cm (3.5 in); speed, 10 000 rpm; lubricant, synthetic tetraester oil; gear temperature, 344 K (160° F); maximum Hertz stress, 1.71×10^9 GPa (248 kpsi).

Figure 4.—Surface fatigue results.

wt % oxidation inhibitor indicated an increase in both 10- and 50-percent fatigue life compared with the lives obtained in the NASA II lubricant tests. And although gear fatigue lives using both the NASA II and NASA IV lubricants show improvement over the life obtained in the

reference oil tests, these results are not statistically significant.

Gear failure was by surface pitting or spalling, which was subsurface in origin on or near the pitch line of the gear teeth. Of the 95 tests run, tooth fracture occurred in

TABLE V.—SUMMARY OF GEAR FATIGUE LIFE RESULTS

[Material, CVM AISI 9310 steel; pitch diameter, 8.89 cm (3.5 in); speed, 10 000 rpm; maximum Hertz stress, 1.71 GPa (248 ksi); lubricant, synthetic tetraester oil with various additives; gear temperature, 344 K (160° F).]

Test lubricant	Gear system life revolutions			Weibull slope	Failure index ^a	Confidence number ^b
	10-percent life	Relative life ratio	50-percent life			
NASA I—Tetraester reference oil + 2.5 percent oxidation inhibitor + 2.1 percent corrosion inhibitor	7.61 × 10 ⁶	1.0	31.0 × 10 ⁶	1.34	30 out of 30	--
NASA II—Same as NASA I + 0.1 percent sulfur-type load-carrying additive	9.26	1.2	65.6	.96	22 out of 23	57
NASA III—Same as NASA I + 0.1 percent phosphorous-type load-carrying additive	19.8	2.6	67.1	1.55	20 out of 20	92
NASA IV—Tetraester reference oil + 0.5 percent oxidation inhibitor + 0.1 percent sulfur-type load-carrying additive	12.5	1.6	73.8	1.06	21 out of 21	71

^aNumber of fatigue failures out of number tested.

^bPercentage of time that 10-percent life obtained using the base oil only will have the same relation to the 10-percent life obtained using oil with a load-carrying additive.

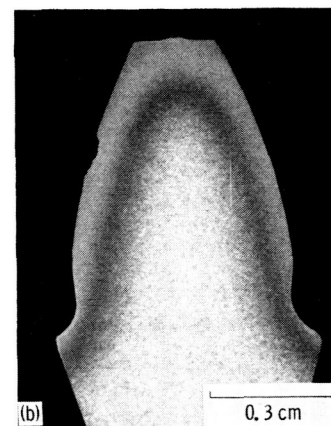
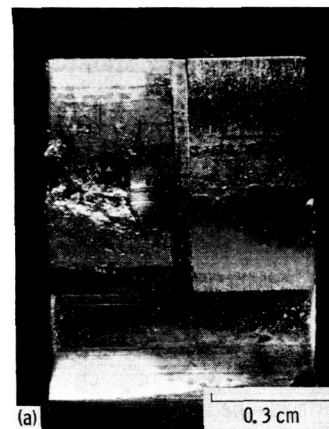
10 of them. However, examination indicated that these fractures were the result of prior fatigue spalls on the tooth surface. A typical fatigue spall is shown in figure 5.

Comparison with Rolling-Element Fatigue Tests

The effect of surface reactive additives on several bearing steels was investigated in a four-ball tester (ref. 12). These tests were run under very severe lubricant film conditions where significant surface film effects would be expected. The limiting life in the majority of these tests was from surface distress and not rolling-element fatigue. Either beneficial or detrimental effects on life could be obtained with each of several additives, depending on the choice of steel.

The experiments of reference 12 were repeated in the NASA five-ball fatigue tester at a lower Hertzian stress level using the same base oil with and without surface reactive additives (ref. 13). In these tests surface reactive additives were found to be detrimental to rolling-element fatigue life. The additives used with the base oil did not change the life ranking of the bearing steels where rolling-element fatigue was of a subsurface origin.

The results of references 12 and 13 indicate a potential negative effect of surface reactive additives on pitting fatigue life. The results reported herein indicate surface reactive (EP) additives have a positive effect on gear tooth pitting fatigue life. The probable reason for the difference in the results could be the combination of contact stress levels and surface temperatures at which the additives react on the gear tooth surfaces. As an example, in the five-ball fatigue tester the surface speed was approximately 344 m/min (1133 ft/min) at a maximum Hertz stress of 5.52 GPa (800 000 psi) and a



(a) Fatigue spall.

(b) Cross section of gear tooth.

Figure 5.—Representative fatigue spall of test gear material CVM AISI 9310 steel. Speed, 10 000 rpm; lubricant, tetraester oil with additive package (reference oil).

bulk temperature of approximately 350 K (170° F) (ref. 14). For the spur gears reported herein, the maximum Hertz stress was 1.71 GPa (248 000 psi), the pitch-line velocity was 2800 m/min (9186 ft/min), and the bulk temperature was 344 K (160° F). Because of the higher velocities at the gear tooth contact, contact temperatures at least 50 K (90° F) higher than the bulk temperatures have been measured (ref. 15). These temperatures are in the range to promote the chemical surface reactions necessary to form a beneficial film on the gear tooth surface (ref. 16). In the five-ball tester the temperatures may have been too low to form a beneficial reactive film. However, this does explain why a negative life effect was observed.

Figure 6 is a series of spot-mode Auger spectra which are characteristic of the surfaces after the first one or two atomic layers have been removed by sputter etching (~ 10 sec). The first spectra is that of the unused gear (fig. 6(a)); the peaks associated with argon, carbon, oxygen, and iron are identified. Argon is present due to the imbedding of the sputtered ions in the sample and is therefore an artifact.

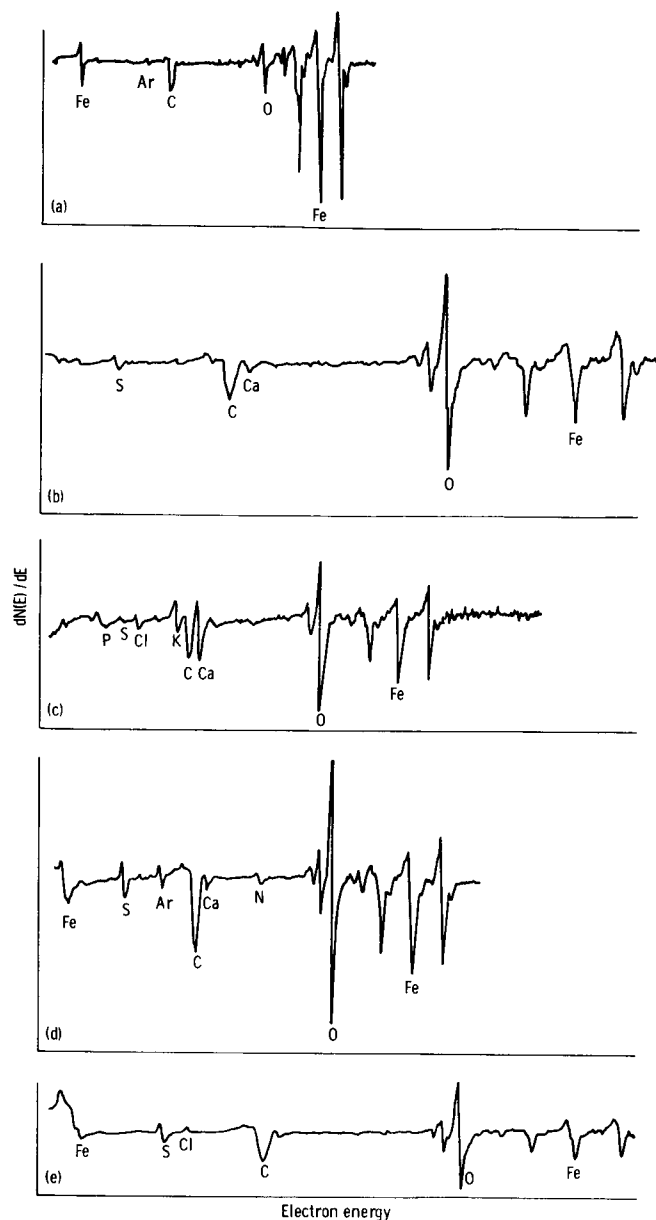
Figure 6(b) shows a spectrum of a gear tooth surface which was tested in the reference (NASA I) oil containing the full oxidation, corrosion, and metal passivation additive package. In addition to the elements shown in figure 6(a), sulfur and calcium are identified. The spectrum in figure 6(c) is for a tooth surface of a gear tested in the phosphorus additive oil (NASA III). In addition to the elements mentioned previously, chlorine, potassium, and phosphorus are identified.

Although Auger spectra generally give information only about the concentration of the elements, it is possible, in some cases, to identify the chemical state by a shift in the energy of the peak or a change in its shape. Here the phosphorous peak energy and shape indicate that it is bound to oxygen in the form of a phosphate (ref. 17).

The spectrum in figure 6(d) is for a tooth surface of a gear run in the NASA II oil which had the sulfur-type EP additive. The same elements as those in figure 6(c) are shown but with the phosphate replaced by an intense sulfur line. The energy and shape of the sulfur line indicate a form of a sulfur (S^{-2}) complex, which is probably bound to the iron as ferrous sulfide (FeS) (ref. 18).

The spectrum in figure 6(e) is for a gear tooth surface run in NASA IV oil without a corrosion inhibitor or metal passivation additives but with the sulfur-type EP and 0.5 percent of the oxidation inhibitor. No phosphorus or nitrogen are shown, but all of the previously observed elements are present.

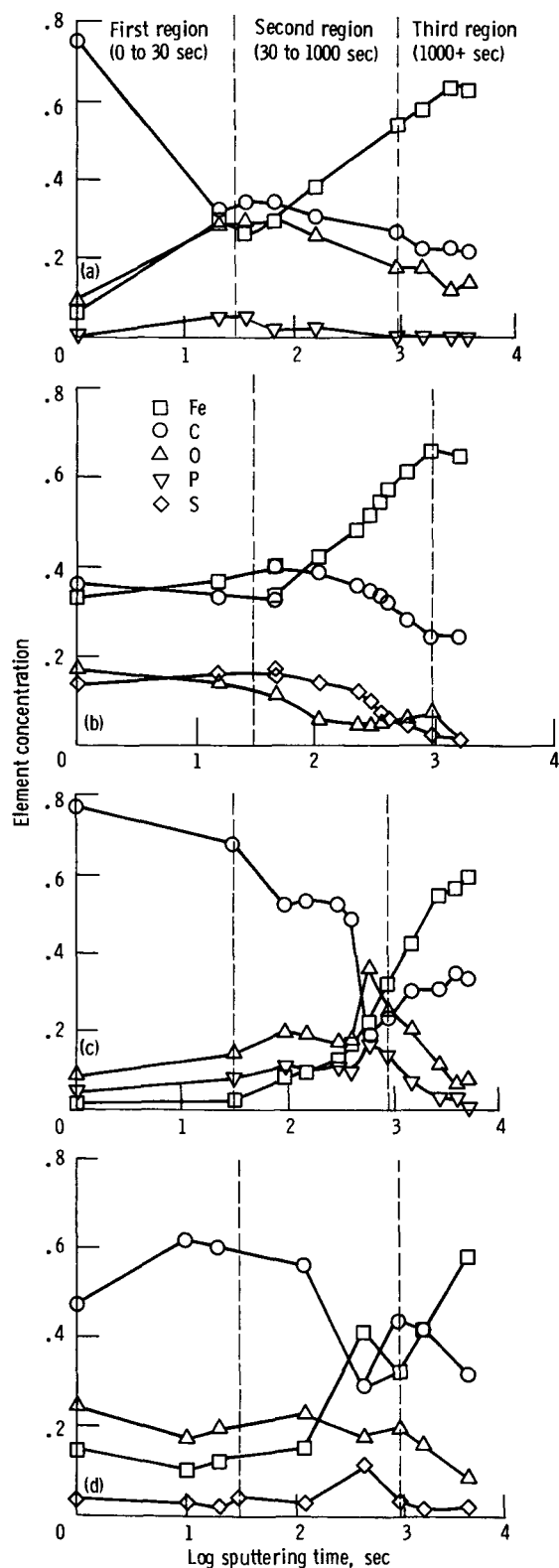
Spectra taken at a series of sputtering times were used to generate the depth profiles shown in figure 7. The concentration of each identified element is plotted as a function of the log of the sputtering time. The element



(a) Tooth surface of unrun gear.
 (b) Tooth surface of gear tested in NASA I (reference) oil.
 (c) Tooth surface of gear tested in NASA III oil.
 (d) Tooth surface of gear run in NASA II oil.
 (e) Tooth surface of gear run in NASA IV oil.

Figure 6.—Auger spectra of gear tooth surfaces after 10 seconds of sputter etching.

concentrations were determined using the procedure described in reference 19. The depth below the original surface at the end of each run can be determined if the sputtering rate (which was constant throughout) is known. Although the sputtering rate could not be measured accurately, it was estimated to be 7 Å/min ($7 \times 10^4 \mu\text{m}/\text{min}$) based on the ion current density and the sputtering rate values given in the literature (ref. 20).



(a) Gear run in NASA I (reference) oil.
 (b) Gear run in NASA II oil.
 (c) Gear run in NASA III oil.
 (d) Gear run in NASA IV oil.

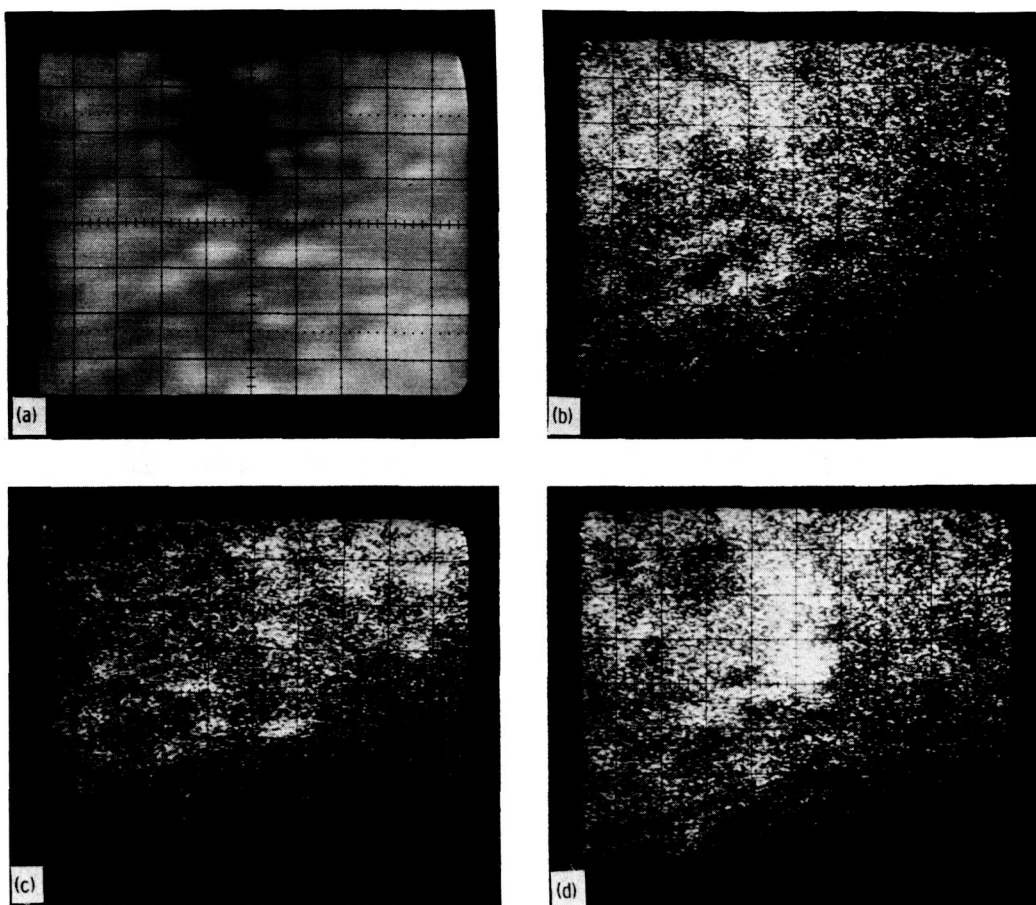
Figure 7.—Depth profile of gear tooth surface after test showing concentration of various elements as function of sputtering time.

To indicate which elements were present on the gear tooth surface as a function of sputtering time, the depth profile was divided into three regions (fig. 7(a)). In the first region (0 to 30 sec sputtering time), the composition observed was that prior to the start of sputtering and the transition to the composition previously discussed during the sputter cleaning phase. All the gear tooth surfaces show large amounts of carbon (C) at the end of the first region in addition to varying amounts of iron (Fe) and oxygen (O). Additionally, in the second region (30 to 1000 sec sputtering time), significant amounts of sulfur (figs. 7(b) and (d)) and phosphorus (fig. 7(c)) are in evidence. These are in the form of iron sulfide (FeS) and a phosphate ion (PO_3^-) as expected for the sulfur and phosphorus EP additives that form the chemically reactive surface films. The small amount of phosphorus (P) appearing on the tooth surface (shown in fig. 7(a)) is probably from the tricresyl phosphate (TCP) metal passivator in the base oil.

At the end of the third region (1000+ sec sputtering time), only iron (Fe), carbon (C), and oxygen (O) are observed. This indicates that, for the most part, all surface films have been sputtered away. Based on a calculated sputtering rate of $7 \text{ \AA}/\text{min}$, the thickness of the FeS film was estimated to be 200 \AA (0.79 \mu in) between sputtering times of 30 to 1585 sec (fig. 7(b)). In the same manner, the thickness of the phosphate (PO_3^-) film was estimated to be 400 \AA (1.58 \mu in) between 30 and 3162 sec. The film thicknesses could vary as much as ± 1.5 times these estimated values. Although the thickness of boundary or EP reactive films containing these elements ranges from 100 to 10 000 \AA (0.40 to 40 \mu in) (ref. 1), quantitative conclusions cannot be made.

Figure 8 shows a series of images of the tooth surfaces of a gear tested in the reference oil after 120 sec of sputtering. A secondary electron image (SED) is shown in figure 8(a). The contrast mechanism is the variation of the secondary electron yield over the surface. This same mechanism was used to obtain images in a standard scanning electron microscope. The secondary yield is influenced by both the surface topology and the chemistry of the surface.

Another contrast mechanism is used to distinguish clearly the spacial variation of the surface chemistry. The Auger system is configured to detect only those electrons which have an energy corresponding to an element of interest. For these images (SAM) bright corresponds to an increased concentration. Therefore, the brighter areas of the SED image can be identified as to their chemistries by referring to the SAM images that accompany it. Figure 8(b) is a scan of the same area where only the iron-rich regions appear white. A comparison of the two images shows that the bright areas in the SED image (fig. 8(a)) are relatively iron poor. Similarly, the carbon image in figure 8(c) and the oxygen image in figure 8(d) show the same areas on the SED image to be poor in oxygen



(a) Secondary electron image (SED) showing variation in electron yield over surface.
 (b) Iron rich regions of same tooth surface shown in (a).
 (c) Carbon rich regions.
 (d) Oxygen rich regions.

Figure 8.—Series of images of gear tooth surfaces run in the base 9756 oil. Gear temperature, 344 K (160° F); maximum Hertz stress, 1.71 GPa (248 000 psi); gear speed, 10 000 rpm.

and rich in carbon. All this leads to the conclusion that the surface layer is nonuniform in thickness. And this suggests that protective films are formed by the reaction of the additives with the surface in response to some spatially varying environmental factor (i.e., mechanical load). Images made of the tooth surfaces of the gear run in the three other lubricants gave similar results.

Summary of Results

Surface fatigue endurance tests were conducted with CVM AISI 9310 gears using a synthetic tetraester oil with oxidation and corrosion inhibitors and an antiwear additive as the lubricant (reference oil). The lubricant conformed to MIL-L-23699 specifications. The tests were divided into four groups. In three of the groups, a 0.1 wt % sulfur- or phosphate-type chemically reactive extreme pressure (EP) additive was added to the base oil

to enhance gear fatigue life. In the fourth group, the reference oil was used as a control.

The gear pitch diameter was 8.89 cm (3.5 in). Test conditions were a gear temperature of 344 K (160° F), a maximum Hertz stress of 1.71 GPa (248 000 psi), and a speed of 10 000 rpm, which gave a pitch-line velocity of 2800 m/min (9163 ft/min).

The following results were obtained:

(1) The 10-percent surface (pitting) fatigue life of the gears tested with the 0.1 wt % phosphate EP additive was 2.6 times that for the gears tested with the tetraester reference oil. These results were statistically significant.

(2) The fatigue lives of gears using the 0.1 wt % sulfur EP additive in the oil showed an improvement in 10- and 50-percent fatigue lives over the gear lives obtained with the reference oil. However, these results were not considered to be statistically significant.

(3) Scanning Auger microscope (SAM) images of the gear tooth surfaces made after testing showed that gears

tested with the 0.1 wt % sulfur and 0.1 wt % phosphorus EP additives in the oil had reactive surface films that were 200 to 400 Å (0.8 to 1.6 μin) thick.

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