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SUMMARY

Rolling-element fatigue tests were run in rolling-contact (RC) rigs at four speeds with three traction fluids and an automatic transmission fluid. Shaft speeds were 5000, 10 000, 25 000, and 50 000 rpm. All tests were run at a maximum Hertz stress of 4.83 GPa (700 000 psi) and a lubricant bulk temperature of 297±3 K (75°±5° F). From 10 to 29 tests were run for each speed-lubricant combination. The life results were analyzed according to Weibull statistics.

Rolling-element fatigue life increased with increased speed for all four lubricants tested. Lives at 5000 and 10 000 rpm were not significantly different, but life increased greatly at 25 000 and 50 000 rpm for each lubricant. The life data tended to follow published life-versus-lubricant-film-parameter curves, except that the data did not extend significantly into the higher lubricant film parameter range, where life tends to approach a maximum value. No significant differences in failure mode or running track appearance were observed with any of the speed-lubricant combinations.

INTRODUCTION

Transmissions that use traction to transmit power are now receiving considerable attention for advanced drive systems (refs. 1 and 2). In these systems the tractive and fatigue life effects of the lubricant largely dictate the size and expected life of a transmission. Special synthetic fluids have been developed to maximize the tractive forces generated in the contact. Limited fatigue data generated with these traction fluids show them to provide fatigue lives comparable to or, in some cases, better than those provided by other conventional oils (refs. 3 to 6). In references 5 and 6, accelerated rolling-element fatigue tests showed that two synthetic traction fluids produced fatigue lives that were statistically equivalent to the lives obtained with the reference tetraester oil. These tests were conducted on a five-ball fatigue tester at a maximum Hertz stress of 5.52 GPa (800 000 psi) and at a constant shaft speed of 10 000 rpm, producing a surface velocity of 4.4 m/s (860 ft/min). No attempt was made to vary the elastohydrodynamic (EHD) film thickness and thus determine its possible effect on fatigue life.

A new high-speed rolling contact (RC) rig has been developed that is capable of varying speeds up to 50 000 rpm (ref. 7). Maximum operating speed of a standard RC rig is 12 500 rpm. The high-speed rig allows testing to higher surface speeds, up to 25 m/s (5000 ft/min), which are of more interest for a greater variety of traction drive systems. Furthermore, the high-speed rig also allows testing at various EHD film thickness values. An increase in EHD film thickness corresponds to an increase in the lubricant film parameter Λ, which is defined as the ratio of the EHD film thickness to the composite roughnesses of the two surfaces in contact. This parameter is related to the amount of surface-to-surface interaction in rolling-element contacts (ref. 8). When the Λ ratio is approximately 4 or greater, surface contact is virtually zero. The lubricant film parameter Λ was first related to the fatigue life of rolling-element bearings by Tallian (ref. 9). Subsequently, after additional experimental confirmation, the effect of Λ on bearing fatigue life, as shown in figure 1, was incorporated in an ASME design guide (ref. 10).

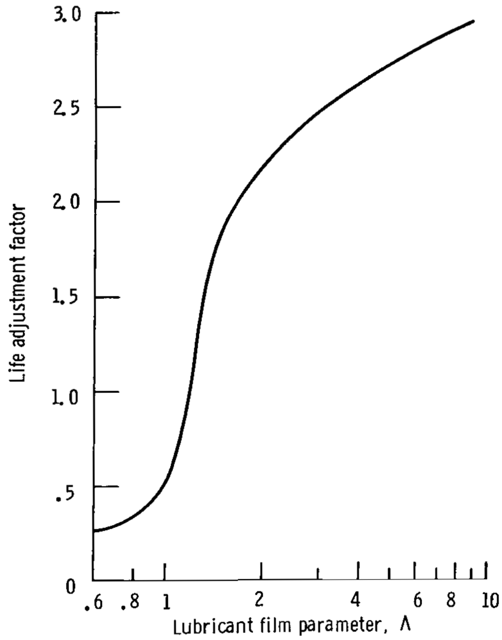

Figure 1. - Effect of lubricant film parameter on rolling-element fatigue life as incorporated in ASME Design Guide (ref. 10).

The new high-speed RC rig appeared to be an ideal accelerated test device in which to compare rolling-element fatigue lives with various traction fluids over a range of Λ conditions that could be expected in traction drive contacts. In addition, the contacts in the RC rig are nearly in pure rolling with virtually no spin. This is unlike the contact conditions in the five-ball fatigue tester. The contacts between the upper ball and the four lower balls in the five-ball tester simulate the contacts between balls and raceways of angular-contact ball bearings and as such have significant spin (circumferential slip) velocity. This spinning in the contact causes significant heat generation, as shown in reference 11, where increased operating temperatures were measured with increased contact angles and consequently increased spin velocity (spin velocity increased with the sine of the contact angle). This spin heating was thought to contribute to occasional contact overheating and subsequent surface damage for several of the tests conducted with the traction fluid that contained a zinc dialkyl dithiophosphate (ZDDP) antiwear additive (refs. 5 and 6). The combination of the high contact pressure and the traction fluid's high spin heating was believed to have aggravated the overreactive chemical effect of the additive. It was anticipated that an alternative accelerated fatigue tester, such as the RC rig, that has contacts with essentially no spin might eliminate this erratic test behavior if this hypothesis was correct.

The objectives of the effort reported herein were (1) to determine the rolling-element fatigue life in the standard and high-speed RC rigs with four synthetic lubricants, including the two traction fluids reported in references 5 and 6, at speeds ranging from 5000 to 50 000 rpm, (2) to evaluate the effects of speed and the film parameter Λ on the experimental rolling-element fatigue life, and (3) to observe whether the previously experienced overheating (refs. 5 and 6) occurs in the nearly pure rolling contacts of the RC rig.

TEST LUBRICANTS AND MATERIALS

The lubricants used in this study consisted of three traction fluids and an automatic transmission fluid. Properties of these lubricants are given in table I. Two of the traction fluids were the same as those reported in references 5 and 6. These were both from the same cycloaliphatic hydrocarbon base stock but contained different additives. The lower viscosity fluid, traction fluid 1, contained only an oxidation inhibitor. Traction fluid 2 contained an oxidation inhibitor, a polymethacrylate viscosity improver, an antiwear additive, and an antifoam additive. The antiwear additive, zinc dialkyl dithiophosphate, is common to many automotive oils and transmission fluids. Traction fluid 3 was a proprietary blend of synthetic hydrocarbons formulated with an additive package similar to one used in automatic transmission fluids. The automatic transmission fluid used in these tests met the specifications of reference 12. The viscosity-temperature characteristics of these fluids are compared in figure 2.

The test bars used in the RC rig tests were made from a single heat of consumable-electrode, vacuum-melted AISI 52100 steel hardened to Rockwell C 60 to 62. They were 76.2 mm (3 in.) long and were ground to a diameter of 9.5 mm (0.375 in.) with a surface finish of 0.1 to 0.2 μm (4 to 8 μin.) centerline average (cla). The contacting idler rollers were made from vacuum-induction-melted, vacuum-arc-remelted (VIM-VAR) AISI M-50 hardened to Rockwell C 62 to 64. The rollers were ground to a diameter of 190 mm (7.5 in.) with a crown radius of 6.35 mm (0.25 in.) and a surface finish of 0.15 to 0.2 μm (6 to 8 μin.) cla.

TABLE I. - TEST LUBRICANT PROPERTIES

Property	Lubricant			
	Traction fluid 1	Traction fluid 2	Traction fluid 3	Automatic transmission fluid
Kinematic viscosity, cm^2/s (cS) at -				
311 K (100° F)	0.23(23)	0.34(34)	0.415(41.5)	0.356(35.6)
372 K (210° F)	0.037(3.7)	0.056(5.6)	0.054(5.4)	0.069(6.9)
Viscosity index	----------	----------	55	162
Flashpoint, K (°F)	422(300)	435(325)	408(275)	478(400)
Fire point, K (°F)	435(325)	447(345)	428(310)	-----------
Autoignition temperature, K (°F)	589(600)	600(620)	-----------	-----------
Pour point, K (°F)	230(-45)	236(-35)	236(-35)	228(-50)
Specific gravity at 311 K (100° F)	0.886	0.889	0.888	0.860

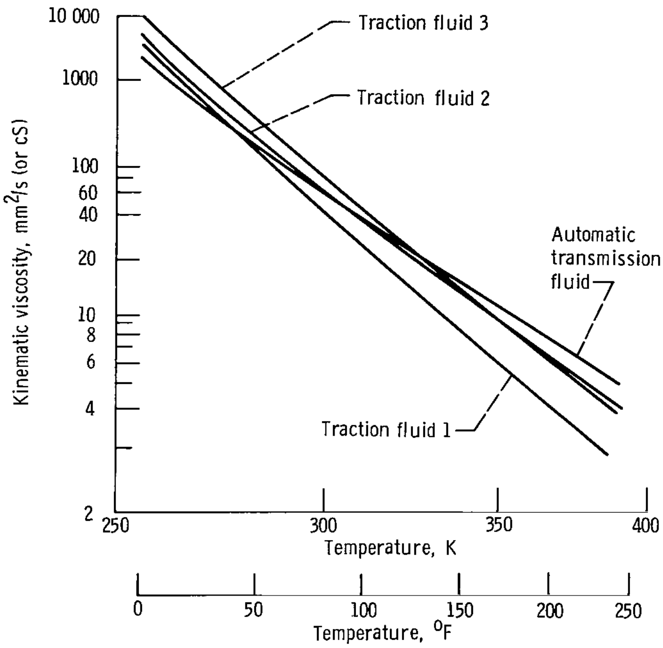

Figure 2. - ASTM chart of test-lubricant kinematic viscosity as a function of temperature.

APPARATUS AND PROCEDURE

High-Speed Rolling Contact Fatigue Test Rig

The high-speed rolling contact fatigue test rig (RC rig) is shown in figure 3. This rig was first described in reference 7 and is the same in principle as the standard rolling-contact fatigue rig. The high-speed RC rig uses an electric motor to drive an air bearing spindle that supports the test bar in a precision chuck to speeds of 50 000 rpm. As in the standard rig the load is applied by closing the two idler rollers against the test bar by using a micrometer-threaded turnbuckle and a calibrated load cell. Lubrication is supplied by a drip feed system by using a needle valve to control flow rate. Several tests can be made on one test bar by indexing the bar in the axial direction relative to the idler rollers.

In this test program tests were run at four speeds. The standard RC rig was used for tests at 5000 and 10 000 rpm, and the high-speed rig was used for tests at 25 000 and 50 000 rpm. All tests were performed with a lubricant bulk temperature of 297±3 K (75°±5° F) and at a maximum Hertz stress of 4.83 GPa (700 000 psi). The temperature of the test bar in the area of the roller contact was measured with an infrared pyrometer.

Method of Presenting Fatigue Results

The total test time for each specimen was recorded and converted to total stress cycles. The statistical methods of reference 13 for analyzing rolling-element fatigue data were used to obtain a plot of the log-log of the reciprocal of the probability of survival as a function of the log of stress cycles to failure (Weibull coordinates). For convenience, the

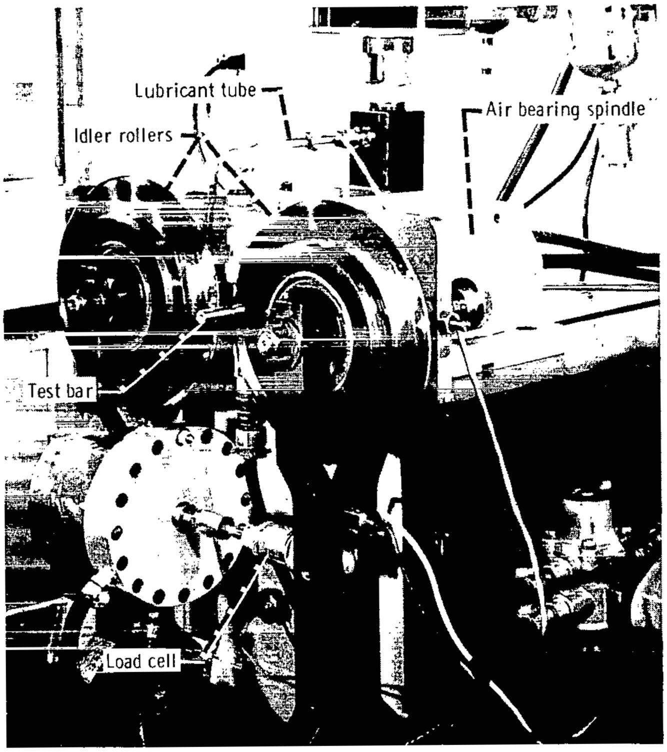

Figure 3. - High-speed rolling-contact fatigue tester (RC rig).

ordinate is graduated in statistical percent of specimens failed. Where high reliability is of main importance, the interest is in early failures. For these comparisons, the 10-percent life on the Weibull plot was used. The 10-percent life is the number of stress cycles within which 10 percent of the specimens can be expected to fail. This 10-percent life is equivalent to a 90-percent probability of survival. The failure index indicates the number of specimens that failed out of those tested. At least 10 tests were run with each lubricant at each speed.

RESULTS AND DISCUSSION

Fatigue Results

Rolling-element fatigue tests were run in RC rigs at four speeds with each of four lubricants. The results are plotted on Weibull coordinates in figures 4 to 7 and are summarized in table II. Life generally increased with speed for all four lubricants.

The 10-percent lives from figures 4 to 7 are plotted in figure 8 and show the continuous increase in life with speed for all four lubricants. The difference in lives at 5000 and 10 000 rpm was small and insignificant. At 25 000 and 50 000 rpm, the life increase with increased speed was dramatic. For traction fluids 1 and 2, life increased continuously with speed. The significance of the data point at 25 000 rpm for traction fluid 3 is questionable and probably overestimated since only five failures were obtained in this test series, and the point appears to be out of line with the rest of the data. The 10-percent lives with the automatic transmission fluid (ATF) rose very rapidly at 25 000 rpm but appeared to level off at

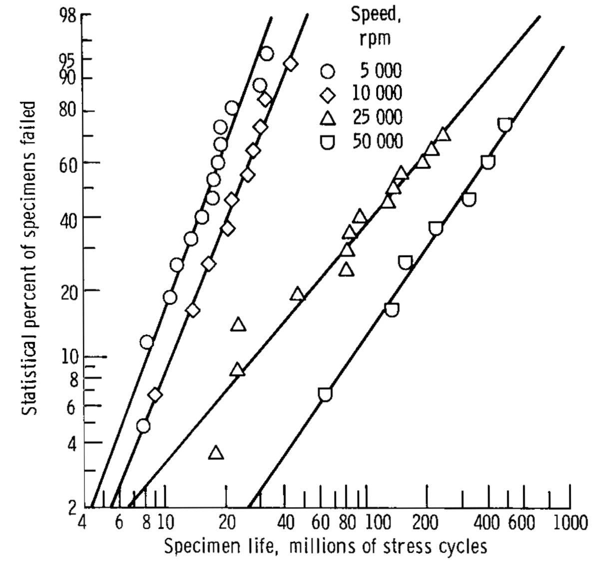

Figure 4. - Rolling-element fatigue life in rolling-contact rigs with traction fluid 1. Maximum Hertz stress, 4.83 GPa (700 000 psi); lubricant bulk temperature, 297 K (75^{0} F).

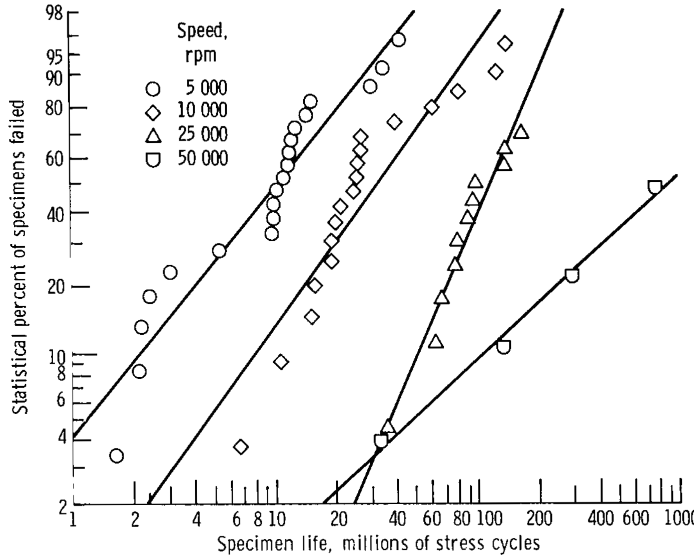

Figure 5. - Rolling-element fatigue life in rolling-contact rigs with traction fluid 2. Maximum Hertz stress, 4.83 GPa (700 000 psi); lubricant bulk temperature, 297 K (75^{0} F).

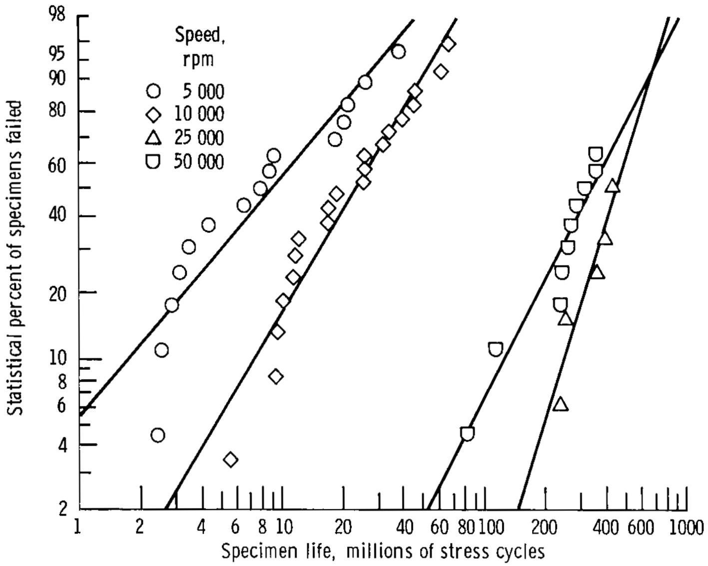

Figure 6. - Rolling-element fatigue life in rolling contact rigs with traction fluid 3. Maximum Hertz stress, 4.83 GPa (700 000 psi); lubricant bulk temperature, 297 K (75^{0} F).

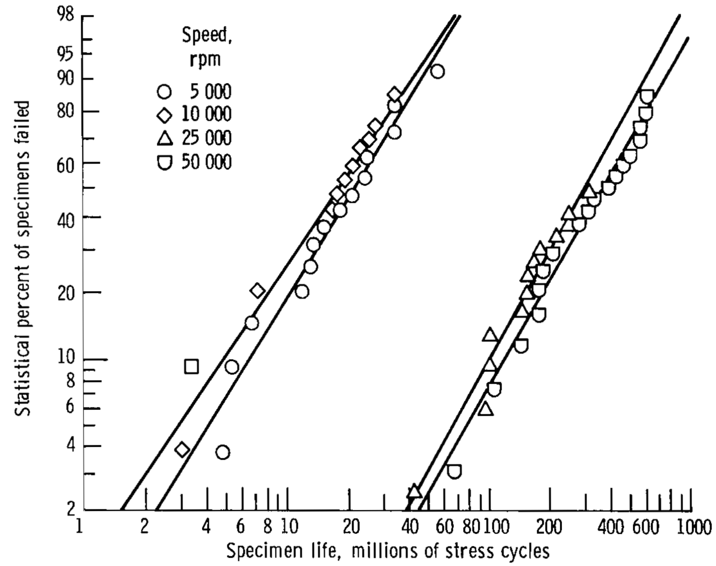

Figure 7. - Rolling-element fatigue life in rolling-contact rigs with automatic transmission fluid. Maximum Hertz stress, 4.83 GPa (700 000 psi); lubricant bulk temperature, 297 K (75^{0} F).

TABLE II. - ROLLING-ELEMENT FATIGUE LIFE WITH FOUR LUBRICANTS AT FOUR SPEEDS IN ROLLING-CONTACT RIG

[Maximum Hertz stress, 4.83 GPa (700 000 psi); lubricant bulk temperature, 297 K (75° F).]

Lubricant	Speed, rpm	Rolling-element fatigue life, millions of stress cycles		Weibull slope	Failure index[a]
		10-Percent life	50-Percent life		
Traction fluid 1	5 000	8.4	17.4	2.58	14 out of 14
	10 000	11.0	23.8	2.44	10 out of 10
	25 000	27.5	140.9	1.15	14 out of 19
	50 000	84.5	328.1	1.39	7 out of 10
Traction fluid 2	5 000	2.1	10.1	1.19	20 out of 20
	10 000	7.8	32.1	1.33	18 out of 18
	25 000	51.1	120.4	2.20	11 out of 15
	50 000	106.3	880.1	.89	4 out of 17
Traction fluid 3	5 000	1.8	9.2	1.15	15 out of 15
	10 000	7.4	23.5	1.62	20 out of 20
	25 000	255.9	462.5	3.18	5 out of 11
	50 000	126.2	343.5	1.88	10 out of 15
Automatic transmission fluid	5 000	6.6	22.1	1.55	14 out of 18
	10 000	4.9	18.6	1.41	16 out of 18
	25 000	101.1	301.0	1.73	13 out of 29
	50 000	122.9	375.1	1.69	19 out of 23

[a] Number of failures out of total number of tests.

50 000 rpm. The curves in figure 8 are drawn to be consistent with those of figure 9, which take into account lubricant film thickness and its variation with speed, as shown in the following section.

Lubricant Film Parameter Effects

Some increase in life with higher speeds was expected since the film parameter Λ becomes larger at higher speeds because of the increase in EHD film thickness. The increase of film thickness for a given lubricant is also dependent on temperature, since temperature affects the lubricant viscosity at the inlet to the bar-roller contact. The lubricant bulk temperature was maintained constant for all the tests at 297±3 K (75°±5° F). With each of the four lubricants the temperature of the test bar was measured with an infrared pyrometer. The pyrometer was focused on the test bar running track between the load rollers. There was little difference in temperature measured with the four lubricants at each speed (within ±2 deg K (3° deg F)), but there was a consistent increase in temperature with speed. Average temperatures at each speed were as follows: 5000 rpm, 300 K (80° F); 10 000 rpm, 301 K (82° F); 25 000 rpm, 308 K (95° F); and 50 000 rpm, 318 K (113° F).

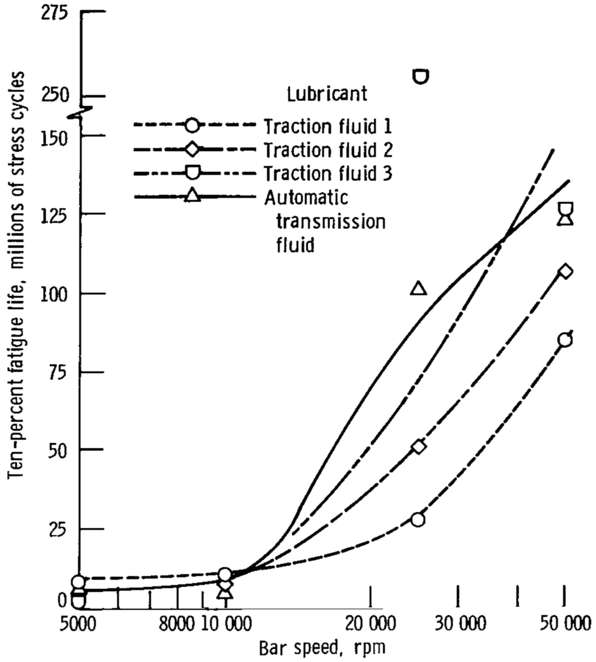

Figure 8. - Effect of bar speed on fatigue life. Maximum Hertz stress, 4.83 GPa (700 000 psi); lubricant bulk temperature, 297 K (75° F).

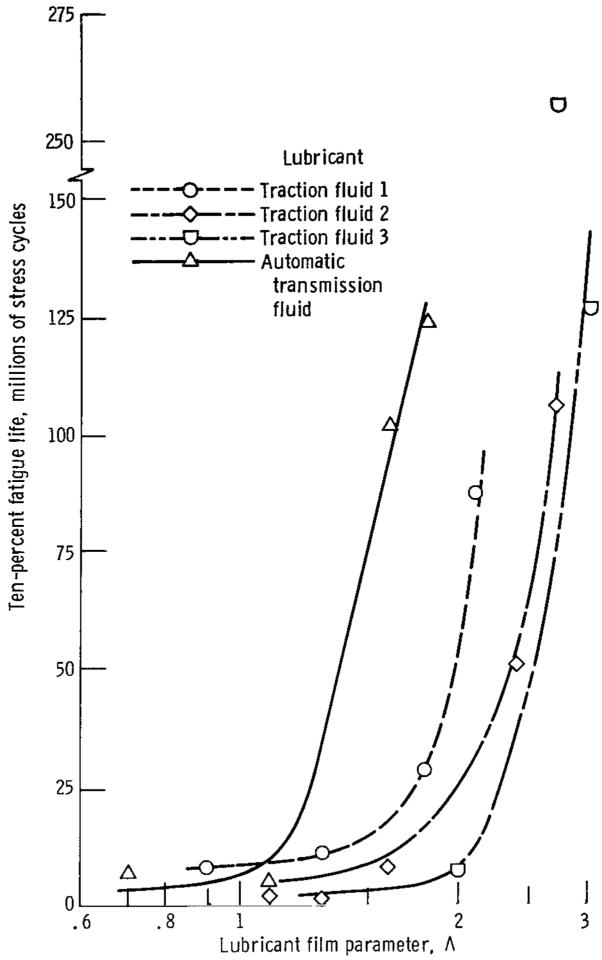

Figure 9. - Effect of lubricant film parameter on fatigue life. Maximum Hertz stress, 4.83 GPa (700 000 psi); lubricant bulk temperature, 297 K (75° F).

The EHD film thickness, assuming that these temperatures are the lubricant temperature at the inlet to the bar-roller contact, was calculated by using the equations of reference 14. The lubricant film parameter Λ was then calculated for each lubricant and speed condition. The results are shown in table III. The experimental 10-percent lives are shown in figure 9 as a function of these calculated Λ values.

These curves show the very high slope similar to that of figure 1 for Λ between 1 and 2, which is considered the range of transition between boundary and full-EHD lubrication. The curve for the ATF in figure 9 slopes upward in this range, but the curves for the traction fluids show this transition at Λ between 2 and 3. These Λ values for the traction fluids may be somewhat optimistic because of the limitation of the isothermal EHD theory, the effects of the internal heating occurring at the high contact stress in the RC rig, and effects of pressure-viscosity coefficient to be discussed in a later section.

The general shape of the curves tends to confirm that as speed was increased above 10 000 rpm in the RC rig, the EHD film thickness increased, and the contact lubrication regime changed from predominantly boundary to the transition between boundary and EHD. It is also apparent that within the range of the present data, the full EHD film range was not reached,

TABLE III. - CALCULATED EHD FILM THICKNESS AND LUBRICANT FILM PARAMETER WITH FOUR LUBRICANTS AT FOUR SPEEDS IN ROLLING-CONTACT RIG

Lubricant	Speed, rpm	EHD film thickness		Film parameter, Λ
		μm	μin.	
Traction fluid 1	5 000	0.20	8	0.9
	10 000	.30	12	1.3
	25 000	.43	17	1.8
	50 000	.48	19	2.1
Traction fluid 2	5 000	0.25	10	1.1
	10 000	.38	15	1.6
	25 000	.56	22	2.4
	50 000	.64	25	2.7
Traction fluid 3	5 000	0.30	12	1.3
	10 000	.46	18	2.0
	25 000	.63	25	2.7
	50 000	.71	28	3.0
Automatic transmission fluid	5 000	0.15	6	0.7
	10 000	.25	10	1.1
	25 000	.38	15	1.6
	50 000	.43	17	1.8

since the experimental curves do not level off as does the curve of figure 1. It was not expected that life would continue to increase indefinitely with Λ, since experimental data published by Takata (ref. 15) and Hobbs (ref. 16) tend to level off for Λ above 3.

Also of significance are the large life differences between the very low Λ range and the transition range in figure 9. The 10-percent lives with all four lubricants at speeds of 5000 and 10 000 rpm were less than 11 million stress cycles (table II). At these speeds there is a large amount of surface-to-surface interaction, and fatigue life is only a small fraction of what it is in the partial and full EHD regimes ($\Lambda > 2$). In the very low Λ regime, several factors may be expected to affect rolling-element fatigue life. These factors include lubricant and additive chemical effects and, as discussed by Tallian (ref. 17), surface traction and asperity slope.

Pressure-Viscosity Coefficient Effects

The calculated range of Λ where the ATF data transitions toward the full EHD regime was significantly less than that for the traction fluids. This difference between the lubricants was not expected since the transition to a full-EHD condition should occur in the same Λ range as long as the identical contact surfaces are used.

The difference may, however, be due to the lack of sufficient knowledge of lubricant properties, in particular the pressure-viscosity coefficient α. The film thickness equation of reference 14 shows that EHD film thickness is proportional to $\alpha^{0.49}$. The values of α for traction fluids are significantly higher than for most other lubricants at temperatures less than about 322 K (120° F) based on capillary viscometer data at low pressures (less than 0.6 GPa (80 000 psi)) from reference 18. For ATF, published data were not available for α, but a typical value (or range of values for the various temperatures) was assumed on the basis of data for similar types of lubricants from reference 18. The published values for an early formulation of traction fluids 1 and 2 are approximately 2.4 times those assumed for the ATF.

The curves of figure 9 resulted from using these assumed α values. However, if the values of α for the traction fluid were assumed to be approximately equal to those of the ATF (values which are typical of most common lubricants), the curves of figure 9 for the traction fluids would shift to the left by a factor of $2.4^{0.49}$, or approximately 1.5 on the Λ scale. With this adjustment, all the curves show the transition toward the full EHD regime between $\Lambda = 1$ and $\Lambda = 2$ as shown in figure 10 and are in closer agreement with figure 1.

Such an adjustment may, in fact, be permissible since the value of α and its effect on EHD film thickness at the high Hertzian pressure in the RC rig are not well defined. Furthermore, the significance of using an EHD film thickness equation to predict the extent of separation between two nonsmooth surfaces in the transition region between boundary and EHD lubrication conditions is not clear. If it is assumed that the life - film parameter trends shown in figure 1 hold for the test lubricants under the operating conditions of the RC rig, the α values of the ATF and traction oils would be approximately the same. At lower contact stress conditions, such as those typical of rolling-element bearings, the high α values found for traction fluids in reference 18 are probably applicable.

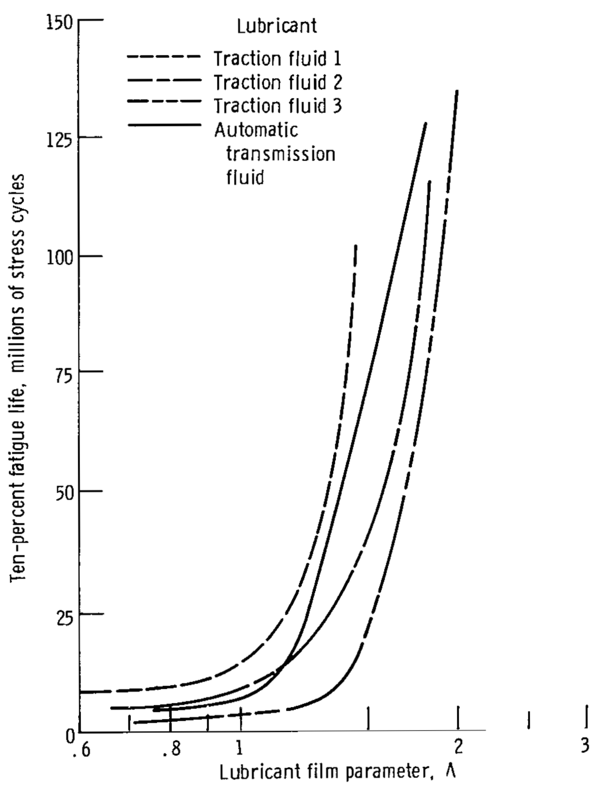

Figure 10. - Effect of lubricant film parameter on fatigue life with adjusted film parameters for traction fluids.

Post-Test Observations

The Λ values in these tests varied from 0.7 to 3.0, which covers a range from a significant surface-to-surface asperity contact to nearly no contact. Observations of the running track on the bar specimens at the various conditions failed to show significant or consistent difference in surface appearance after the tests. Several factors contributed to this lack of definition. Most of the tests resulted in fatigue spalling, which subsequently causes secondary damage to the unfailed portion of the running track from the spall debris. Additionally, there were large differences in the number of stress cycles in the various suspended tests such that a direct and consistent comparison could not be made. Also, the range of Λ values spanned by tests with any one lubricant was relatively small, less than the overall range with all lubricants tested.

The observations of running track post-test condition also showed no significant differences between traction fluids 1 and 2. No premature failures due to surface distress or overheating occurred such as those that were observed with traction fluid 2 in the five-ball tests (refs. 5 and 6). In those tests, the traction fluids ran at a race temperature approximately 8 deg K (15 deg F) higher than did a tetraester fluid. This difference was due to the high traction coefficient of the traction fluids and the high spin velocity in the five-ball tests. In the RC rig tests, where spinning is absent, there was no temperature difference between the traction fluids and the ATF. The ATF is believed to have a lower traction coefficient, similar to that of the tetraester used in references 5 and 6. Unpublished tests in the five-ball tester also show lower temperatures with the ATF than with the traction fluids.

Since the RC rig tests showed no difference in failure mode or track surface condition, it was concluded that the premature failures with traction fluid 2 in the five-ball tests were most likely due to sensitivity of that lubricant to the relatively high spin heating. This sensitivity is most likely due to the overreactive chemical effect of the ZDDP additive as discussed in references 5 and 6.

SUMMARY OF RESULTS

Rolling-element fatigue tests were run in rolling-contact (RC) rigs at four speeds with three traction fluids and an automatic transmission fluid. Shaft speeds were 5000, 10 000, 25 000, and 50 000 rpm. All tests were run at a maximum Hertz stress of 4.83 GPa (700 000 psi) and a lubricant bulk temperature of 297±3 K (75°±5° F). From 10 to 29 tests were run for each speed-lubricant combination. The life results were analyzed according to Weibull statistics. The following results were obtained:

1. Rolling-element fatigue life increased with increased speed for all four lubricants tested. Lives at 5000 and 10 000 rpm were not significantly different, but life increased greatly at 25 000 and 50 000 rpm for each lubricant.

2. The life data tended to follow published life-versus-lubricant-film-parameter curves, except that the data did not extend significantly into the higher film parameter range, where life tends to approach a maximum value.

3. No significant differences in failure mode or running track appearance were observed with any of the speed-lubricant combinations.

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16. Abstract

Rolling-element fatigue tests were run in standard and high-speed rolling-contact rigs at bar speeds from 5000 to 50 000 rpm to determine the effects of speed and lubricant film parameter on rolling-element fatigue life. AISI 52100 test bars were tested at a maximum Hertz stress of 4.83 GPa (700 000 psi) with three traction fluids and an automatic transmission fluid. Rolling-element fatigue life increased with speed, with the greatest increases occurring from 10 000 to 50 000 rpm. The life data tended to follow published life-versus-lubricant-film-parameter data up to a film parameter of approximately 3.

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