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16. Abstract

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ABSTRACT

Gear endurance tests and rolling-element fatigue tests were conducted to compare the performance of spur gears made from AISI 9310, CBS 600 and modified Vasco X-2 and to compare the pitting fatigue lives of these three materials. Gears manufactured from CBS 600 exhibited lives longer than those manufactured from AISI 9310. However, rolling-element fatigue tests resulted in statistically equivalent lives. Modified Vasco X-2 exhibited statistically equivalent lives to AISI 9310. CBS 600 and modified Vasco X-2 gears exhibited the potential of tooth fracture occurring at a tooth surface fatigue pit. Case carburization of all gear surfaces for the modified Vasco X-2 gears results in fracture at the tips of the gears.

INTRODUCTION

Advanced concepts for helicopters, VSTOL aircraft and geared fan jet aircraft engines have created new demands for gear materials having higher temperature operating capability as well as longer life. Current gear materials such as AISI 9310 loose much of their hardness at operating temperatures beyond 394 K (250° F) [1]. Hence, long-term transmission operation beyond this temperature is not feasible.

Several carburizing-type steels have been developed for use in tapered-roller bearings [1-3] in the 478 to 589 K (400° to 600° F) range. Since these are case

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carburized steels with hard surfaces and softer, more tough cores, they may have possible application as gear materials. One of these materials is known as CBS 600 [2]. The material maintains a suitable bearing hardness (Rockwell C 58) to 505 K (450° F) for long-term operation and to 589 K (600° F) for short-time operation [2, 3]. CBS 600 is a low alloy material that has good machinability and curburizes easily. Because of its hot hardness strength and curburizing quality, CBS 600 is promising for use as a gear material in advanced aircraft applications.

Another material that has shown promise for gear application is a material designated as modified Vasco X-2 [4]. This material was used for the gears in the transmission of U.S. Army Heavy Lift Helicopter [4], the Boeing UTTAS helicopter [5], and the YCH-47D helicopter [6]. This material was originally developed as a tool steel and designated H-12 tool steel. The H-12 steel was later modified by lowering the carbon content from 0.35 to 0.24 percent and designated Vasco X-2. This material was a through hardened tool steel. In order to make the Vasco X-2 usable as a gear material, the carbon content was further reduced to 0.13 to 0.16 percent. Thus, the case could be carburized and hardened and the material core would have a fracture toughness that is typically required of a good gear material.

The research reported herein, which is based on the work reported in [1,7], was undertaken to investigate the endurance and failure characteristics of spur gears made from CBS 600 and modified Vasco X-2. The objectives of the research reported herein were to (a) compare the endurance of spur gears made from AISI 9310, CBS 600 and modified Vasco X-2 and (b) compare the rolling-element fatigue lives of the CBS 600 and Vasco X-2 with AISI 9310.

Gear Test Apparatus

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

A schematic of the test rig is shown in Fig. 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 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 are separated at the gearbox shafts by pressurized labyrinth seals. Nitrogen is the seal gas. The test gear lubricant is filtered through a 5-micrometer nominal fiberglass filter. The test lubricant can be heated electrically with an immersion heater. The skin temperature of the heater is controlled to prevent overheating the test lubricant.

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

The belt-driven test rig can be operated at several fixed speeds by changing pulleys. The operating speed for the tests reported herein was 10 000 rpm.

Rolling-Contact (RC) Fatigue Tester

The rolling-contact (RC) fatigue tester is shown in Fig. 2. A cylindrical test bar is mounted in the precision chuck. The drive means attached to the chuck drives the bar which in turn drives two idler disks. Load is applied by closing the disks against the test bar using a micrometer-threaded turnbuckle and a calibrated load cell. Lubrication is supplied by a drop feed system using a needle valve to control the flow rate. Several test runs can be made on one test bar by moving the bar position in the axial direction relative to disk contacts. The test bar is rotated at 12 500 rpm and receives 25 000 stress cycles per minute. The maximum Hertz stress was 4.83×10^9 N/m^2 (700 000 psi).

Test Gears

A photograph of the test gears is shown in Fig. 3. The dimensions of the gears are given in Table 1. All gears have a nominal surface finish on the tooth face of 0.41 micrometer (16 μin.). All the NASA gears except lot A have a standard 20° involute profile with tip relief. The tip relief was 0.0013 centimeter (0.0005 in.) starting at the highest point of single tooth contact. Gears manufactured from lot A of modified Vasco X-2 had no tip relief and were defective from heat treatment. The Boeing Vertol modified Vasco X-2 gears had a dedendum relief of 0.002 centimeter (0.0009 in.) with no tip relief. The Curtis-Wright modified Vasco X-2 gears had no profile modification.

RC Test Bar Specimens

The test specimens for the rolling-contact (RC) fatigue tester were cylindrical bars 7.62 centimeters (3 in.) long with a 0.95-centimeter (0.375-in.) diameter. The surface finish was 0.13 to 0.2 micrometer (5 to 8 μin.) rms.

The large mating disks had a diameter of 19 centimeters (7.5 in.) and a crown radius of 0.635 centimeter (0.25 in.). The surface finish of the disks was the same as the test bars.

Test Materials

AISI 9310 baseline gears and RC bars were manufactured from a single heat of consumable-electrode vacuum melted (CVM) AISI 9310. The chemical composition of this material is given in Table 2. The heat treatment is given in Table 3.

CBS 600. - Two heats of CBS 600 material were used. Lot A was from one heat of air melted material and lots B, C, and D were from a second heat of consumable-electrode vacuum melted (CVM) material. The nominal chemical composition of the material is given in Table 2. The heat treatment for the material is given in Table 3. Lot A was used for the test gears and for one group of RC bars. The case and core properties of the RC bars are given in Table 4.

Modified Vasco X-2. - Four lots of gears were manufactured from three heats of CVM modified Vasco X-2 material. The nominal chemical composition of the material is given in Table 2. The heat treatment is given in Table 3.

Gears manufactured from lots A and B were heat treated to NASA specifications. Both lots were from the same heat of material. Lot A was carburized on all sides of the gear. Lot B was carburized on the gear flanks only. The gears were rough machined 0.38 mm (0.015 in.) oversize before carburizing. This was done so that the outer layer of heavy carbide concentration could be ground off leaving a case depth of 0.71 mm (0.028 in.).

Lot C was from a second heat of material. This lot was heat treated according to the specification of the Curtis-Wright Corp. [8].

Lot D was from the third heat of material. This lot was heat treated to the Boeing Vertol specification, which is assumed to be according to [9,10] under their quality control procedure.

RC test bar specimens were manufactured from the same heat of material as that for lots A and B.

Lubricant

All the gears were lubricated with a single batch of synthetic paraffinic oil. The physical properties of this lubricant are summarized in Table 5. Five percent of an extreme pressure additive, designated Lubrizol 5002 (partial chemical analysis given in Table 5), was added to the lubricant.

The RC test specimens were lubricated with a diester-type lubricant, meeting the MIL-L-7808 specification. The fluid comprised a mixture of two base stocks, a diester plus a (trimethylol propane) polyester. The additives in this fluid included antioxidants, load-carrying additives, metal passivators, a hydrolytic stability additive, and a silicone antifoam additive. The types and levels of the additives were proprietary. The lubricant properties are given in Table 5.

Test Procedure

Gears. - After the test gears were cleaned to remove their protective coating, they were assembled on the test rig. The test gears were run in an offset condition with a 0.30-centimeter (0.120-in.) tooth-surface overlap to give a load surface on the gear face of 0.28 centimeter (0.110 in.), thereby allowing for edge radius of the gear teeth. If both faces of the gears were tested, four fatigue tests could be run for each set of gears. All tests were run-in at a load of 1225 N/cm (700 lb/in.) for 1 hour. The load was then increased to 5784 N/cm (3305 lb/in.) which results in a 1.71×10^{9}-N/m^2 (248 000-psi) pitch-line maximum Hertz stress. At the pitch-line load the tooth bending stress was 0.21×10^{9} N/m^2 (30 000 psi) if plain bending is assumed. However, because there is an offset load there is an additional stress imposed on the tooth bending stress. Combining the bending and torsional moments gives a maximum stress of 0.26×10^{9} N/m^2 (37 000 psi). This bending stress does not include the effects of tip relief which would also increase the bending stress.

Operating the test gears at 10 000 rpm gave a pitch-line velocity of 46.55 meters per second (9163 ft/min). Lubricant was supplied to the inlet mesh at 800 cubic centimeters per minute at 320±6 K ($116^{\circ}\pm10^{\circ}$ F). The lubricant outlet temperature was nearly constant at 350±3 K ($170^{\circ}\pm5^{\circ}$ F). The tests ran continuously (24 hr/day) unless the rig was automatically shut down by the vibration detection transducer, located on the gearbox adjacent to the test gears or completed 500 hours without failure. The lubricant circulated through a 5-micrometer fiberglass filter to remove wear particles. For each test, 3800 cubic centimeters (1 gal) of lubricant were used. At the end of each test, the lubricant and filter element were disgarded. Inlet and outlet oil temperatures were continuously recorded on a strip-chart recorder.

The pitch-line elastohydrodynamic (EHD) film thickness was calculated by the method of [11]. 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 inlet temperature was considerably lower. It is possible that the gear surface temperature was even higher than the oil outlet temperature, especially at the end points of sliding contact. The EHD film thickness for these conditions was computed to be 0.33 micrometer (13 μin.), which gave an initial ratio of film thickness to composite surface roughness (h/σ) or 0.55 at the 1.71×10^{9}-N/m^{2} (248 000-psi) pitch-line maximum Hertz stress.

Each pair of gears were considered as a system and, hence, a single test. Test results were evaluated using the method of Johnson [12].

RC tests. - Fatigue testing was performed in the RC rig. The test bar was installed and the disks were brought against the bar using the turnbuckle. The load applied was sufficient to allow the bar to drive the contacting disks, and the bar was accelerated to the 12 500 rpm test speed.

When the disks and test bar were in thermal equilibrium at a bar temperature of approximately 305 K (90° F), the full load was applied to give the test bar a stress of 4.83×10^{9} N/m^{2} (700 000 psi). When a fatigue failure occurred, the rig and related instrumentation were automatically shut down by a vibration detection system. The axial position of the test bar in the drive chuck was changed to use a new running track before testing was resumed. Test results were also evaluated according to the methods of [12].

RESULTS AND DISCUSSION

Gear Life Results

Four lots of modified Vasco X-2, one lot of air melt CBS 600 and one lot of CVM AISI 9310 spur gears were endurance tested. Test conditions were a tangential tooth load of 5784 newtons per centimeter (3305 lb/in.) which produced a maximum Hertz stress of 1.71×10^9 N/m^2 (248 000 psi) and a speed of 10 000 rpm. The gears failed by classical subsurface pitting fatigue or tooth bending fracture. The pitting fatigue life results of these tests are shown in Figs. 4 and 11 and are summarized in Table 6.

Pitting fatigue life results for the gears made from the CVM AISI 9310 material are shown in Fig. 4(a). The 10- and 50-percent lives were 24×10^6 and 54×10^6 stress cycles (40 and 90 hr), respectively. The failure index (i.e., the number of fatigue failures out of the number of sets tested) was 30 out of 30. A typical fatigue spall that occurs near the pitch line is shown in Fig. 5. This spall is similar to those observed in the rolling-element fatigue tests shown in Fig. 6. The pitch-line pitting is the result of high subsurface shearing stress which develops subsurface cracks. The subsurface originating cracks propagate into a crack net work which results in a fatigue spall that is slightly below the pitch line where the sliding condition is more severe.

Pitting fatigue life results for the gears systems made from the CBS 600 material are shown in Fig. 4(b). The failure index was 2 out of 20. Eighteen (18) tests were suspended after 500 hours of test time. Since only two failures occurred, the life estimate for these tests was determined by assuming the same Weibull slope that was determined for the AISI 9310 data and then by drawing the line through the earliest failure point. The estimated 10- and 50-percent lives determined in this manner were 180×10^6 and 380×10^6 stress cycles (300 and 633 hr), respectively.

A statistical comparison was made of the differences in the gear tooth fatigue life of the CVM AISI 9310 and air-melt CBS 600. These results are summarized in Table 6. The CBS 600 achieved a life at least 7.5 times that of AISI 9310. The confidence number for the difference in life was 99 percent. A confidence number of 95 percent which is equivalent to a 2-sigma confidence level is considered statistically significant. The confidence number indicates the percentage of time the relative lives of the materials will occur in the same order. Based on the rolling-element fatigue tests reported herein, these gear test results would not have been predicted.

One of the fatigue spalls on the CBS 600 gears is shown in Fig. 7(a). A cross section of this fatigue spall is shown in Fig. 7(b). The two gears with pitting failures were run for 6 hours after spalling had occurred. A single tooth bending fracture occurred on each of the gears as a result of the overrun. A fractured tooth is shown in Fig. 8. AISI 9310 gears that were overrun did not fracture.

Four pairs of modified Vasco X-2 gears having the NASA heat treat specification which were carburized on all sides were tested. Several fracture failures occurred, in a short time on each pair of gears tested. Failure was by tooth fracture at the tips of the teeth as shown in Fig. 9.

Two unfailed teeth on a single failed gear were cross-sectioned across the width of the tooth and across the profile. A cross section of the tooth width is shown in Fig. 10(a). The section revealed cracks around the corners of the tooth. Test gears that had not been run were sectioned and similar cracks were found as shown in Fig. 10(b). Because the gears had not been run, it was evident that the cracks developed during heat treatment. It was theoreized that the cracks were caused by expansion of the carburized surface that produced excessive tensile stresses in the core material. All subsequent gears tested did not have the sides and end of the gear teeth carburized.

The modified Vasco X-2 material is somewhat low in fracture toughness even with carefully controlled carburization [13, 14]. Low fracture toughness may result in material fracture under adverse stress conditions. The CBS 600 material has a higher fracture toughness than the modified Vasco X-2 material [2]. However, this material also has the potential to fracture under adverse stress conditions. For both materials it is necessary to exercise very stringent quality control during heat treatment. Unless the prescribed heat treat method is closely followed and controlled, poor carburization will result. This can in turn result in low pitting fatigue life and/or fracture failure of gear teeth.

The pitting fatigue life results for the three lots of gears made from the modified Vasco X-2 are shown in Fig. 11. A statistical comparison was made between the gear tooth pitting fatigue life of the three lots of modified Vasco X-2 gears and the CVM AISI 9310 and is summarized in Table 6. The difference between the pitting fatigue life of the AISI 9310 gears and modified Vasco X-2 lot D having the Boeing Vertol heat treatment gears is statistically insignificant with a confidence number of 80 percent. Lots B and C having the NASA and Curtis-Wright heat treatments, respectively, had statistically lower lives than the AISI 9310 gears. In addition, lot B had fracture failures of several of the gears concurrent with the pitting fatigue failure. A representative fracture failure is shown in Fig. 12.

Of the 12 failed tests of modified Vasco X-2 lot D, five gear sets were deliberately overrun for 8, 10, 16, 30, and 60 hours after the surface fatigue spall had formed. Only one gear subsequently failed by fracture of the teeth after 8 hours (4.8×10^6 stress cycles) in the overrun condition. The fractures portion of the gear is shown in Fig. 13. As in the previous instances for the other heat treat methods, the spall acted as the nucleus of the fracture failure. However, based upon the other overrun tests, the Boeing Vertol heat treat procedure resulted in modified Vasco X-2 gears less susceptible to fracture failure.

Rolling-element fatigue. - Test bars of one lot of CVM modified Vasco X-2, CVM AISI 9310 and four lots of CBS 600 were tested in the rolling-contact (RC) fatigue tester. The CBS 600 comprised one lot of air-melted material and three lots of consumable-electrode melted (CVM) material. Each lot had a separate heat treatment. The bars were tested at a maximum Hertz stress of 4.8×10^9 N/m^2 (700 000 psi) and a bar speed of 12 500 rpm. The tests were run at ambient temperature (no external heat source) with a MIL-L-7808 lubricant. The results of these tests are shown in the Weibull plots of Fig. 14 and are summarized in

Table 7. These data were analyzed according to the methods of [12]. The spalling fatigue failure for CBS 600 shown in Fig. 6 is typical of all three materials.

The three lots of CVM CBS 600 material gave lives exceeding the air-melted CBS 600. There was no statistical difference in the rolling-element fatigue lives between the AISI 9310, CBS 600 and modified Vasco X-2 materials for the conditions reported.

Metallurgical variables. - The major difference which could affect surface fatigue between the AISI 9310 material used for the rolling-element fatigue (RC bar) specimens and for the gears was their respective case hardness. For both the CBS 600 and AISI 9310, the rolling-element (RC bar) specimen nominal case hardness was Rockwell C 61. For the AISI 9310 gears, which were heat treated by a separate vendor, the normal gear case hardness was Rockwell C 58. The case hardness of the CBS 600 gears was Rockwell C 61. It is commonly accepted that component hardness affects the pitting fatigue life of a rolling-element system [15]. Hence, it would be expected that the CBS 600 gears would have a longer life than the AISI 9310 gears. However, based on hardness alone, the difference in life would only be expected to be 20 to 30 percent [15] and not the 650 percent reported herein. Thus, the CBS 600 material exhibits a pitting fatigue life at least equivalent to AISI 9310.

Reference [2] reports good fracture toughness for the CBS 600 material. There are three factors which may have contributed to tooth fracture after pitting occurred on the gear teeth as reported herein. First, the resultant core hardness of Rockwell C 45 is excessive for the CBS 600 and, therefore, makes the material more brittle. Second, the case grain structure has large carbides from a slight amount of excess carbon. This condition would tend to promote bending-type fatigue failure. Third, there was an excessive case depth of 1.47 millimeters (0.058 in.) instead of the desired 0.76 millimeter (0.030 in.). All of these factors can and should be controlled. However, lower amounts of carbon, a lower core hardness, and a lower case depth may not by themselves assure an absence of bending failure when accompanied by surface pitting. Additional research must be undertaken to assure that tooth fracture can be eliminated with reasonable heat-treat procedures.

SUMMARY OF RESULTS

Gear endurance tests and rolling-element fatigue tests were conducted to compare the endurance of spur gears made from AISI 9310, CBS 600 and modified Vasco X-2 and to compare the rolling-element fatigue lives of these three materials. Spur gears manufactured from four lots of modified Vasco X-2, one lot of air melt CBS 600 and one lot of CVM AISI 9310 were endurance tested. Test conditions were a tangential tooth load of 5784 N/cm (3305 lb/in.) which produced a maximum Hertz stress of 1.71×10^{9} N/m^2 (248 000 psi) and a speed of 10 000 rpm. Rolling-element fatigue tests were conducted with RC test bars from one lot of CVM modified Vasco X-2, CVM AISI 9310 and four lots of CBS 600. The test bars were tested at a maximum Hertz stress of 4.83×10^{9} N/m^2 (700 000 psi) and a bar speed of 12 500 rpm. The following results were obtained:

1. Spur gears manufactured from air melt CBS 600 exhibited 10 percent lives statistically longer than CVM AISI 9310 gears. However, rolling-element fatigue tests of CVM CBS 600 and AISI 9310 resulted in statistically equivalent 10 percent lives:

2. The differences in the 10-percent life between the spur gears with long lives manufactured from modified Vasco X-2 and AISI 9310 were not statistically significant. These results were similar to those obtained with the rolling-element fatigue tests.

3. Gears manufactured from both the CBS 600 and modified Vasco X-2 materials exhibited a potential for a surface fatigue spall on the tooth surface acting as a nucleus for a tooth fracture failure. This phenomenon does not occur with gears manufactured from AISI 9310.

4. Case carburization of all the gear surfaces for the modified Vasco X-2 gears resulted in fracture at the tips of the gears. However, carburization of the gear flanks only using a carefully controlled heat-treat procedure, eliminates this failure mode.

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TABLE 1. - GEAR DATA

[Gear tolerance per AGMA class 12.]

Number of teeth	28
Diametral pitch	8
Circular pitch, cm (in.)	0.9975 (0.3927)
Whole depth, cm (in.)	0.762 (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)

TABLE 2. - NOMINAL CHEMICAL COMPOSITION

OF TEST MATERIALS BY PERCENT WEIGHT

Element	AISI 9310	Modified Vasco X-2	CBS 600
Carbon (core)	0.10	0.14	0.19
Manganese	65	.25	.61
Phosphorus	.01	.01	.01
Sulfur	.01	.01	.01
Silicon	.25	.91	1.05
Copper	.11	.07	----
Chromium	1.30	4.90	1.50
Molybdenum	.13	1.36	.95
Vanadium	----	.42	----
Nickel	3.2	.10	.18
Cobalt	----	.02	----
Tungsten	----	1.35	----
Iron	Balance	Balance	Balance

TABLE 3. - HEAT TREAT PROCEDURE FOR MATERIALS TESTED

Step	Process	AISI 9310			Modified Vasco X-2: Lots A and B			Modified Vasco X-2: Lot C			Modified Vasco X-2: Lot D			CBS 600: Gears and RC, lot A			CBS 600: RC, lots B, C, and D		
		K	(°F)	hr	K	(°F)	hr	K	(°F)	hr	K	(°F)	hr	K	(°F)	hr	K	(°F)	hr
1	Rough machine		Yes			Yes			Yes			Yes			---			---	
2	Preclean blast of aluminum oxide		No			No			No			Yes			---			---	
3	Preheat in air		No		1117	(1550)			No			No		866	(1100)	2		---	
4	Preoxidize at temperature		No		1283	(1850)	½		No		1255	(1800)	¾		---			---	
5	Air cool		No			Yes			No			Yes			---			---	
6	Copper plate area not carburized		Yes			Yes			Yes			Yes			---			---	
7	Carburize 0.85 to 1.0 percent C potential	1172	(1650)		1200	(1700)		1200	(1700)	1¾	1200	(1700)	6	1200	(1700)	8	1227	(1750)	13
8	Furnace cool to		No			No		1061	(1450)		1090	(1500)			---			---	
9	Air cool		Yes			Yes			Oil quench			Yes			Oil quench			Oil quench	
10	Stress relieve	922	(1200)	2½		No		422	(300)	2	589	(600)	2	894	(1150)	4	894	(1150)	4
11	Strip copper plate		Yes			Yes			Yes			Yes			---			---	
12	Blast clean aluminum oxide		No			No			No			Yes			---			---	
13	Nickel plate 0.0003 maximum		No			No			No			Yes			---			---	
14	Copper plate 0.001 minimum		Yes			No			No			Yes			---			---	
15	Preheat		No			No		1090	(1500)		1061	(1450)	½		---			---	
16	Austentize	1117	(1550)	2½	1283	(1850)	1	1283	(1850)	2	1283	(1850)	½	1107	(1535)	½	1107	(1535)	½
17	Oil quench		Yes			Yes			Yes			Yes			Yes			Yes	
18	Deep freeze	189	(-120)	3½	200	(-100)	3		No		200	(-100)	3		---			---	
19	Double temper	422	(300)	2 ea	589	(600)	2 ea	589	(600)	2 ea	589	(600)	2 ea	589	(600)	2 ea	(B) 455 (C, D) 589	(360) (600)	2 ea 2 ea
20	Blast clean aluminum oxide		No			No			No			Yes			---			---	
21	Strip copper plate		Yes			No			No			Yes			---			---	
22	Finish grind		Yes			Yes			Yes			Yes			---			---	

TABLE 4. - METALLURGICAL CASE AND CORE CHARACTERISTICS OF ROLLING-CONTACT TEST BARS

Material	Test lot (melt)	Effective[a] case depth, mm (in.)	Case hardness, Rockwell C	Case retained austenite, vol. %	Core	
					Hardness, Rockwell C	Grain size (ASTM number)
CBS 600	A (air melt)	0.76 (0.030)	62.9	22.8	41.0	6-7
	B (CVM)	.84 (.033)	61.7	4.3	↓	7-8
	C (CVM)	.84 (.033)	60.3	3.4	↓	7-8
	D (CVM)	.76 (.030)	61.6	2.1	↓	7-8
AISI 9310	-------- (CVM)	0.84 (0.033)	61.4	11.2	38.0	---
Modified Vasco X-2	-------- (CVM)	1.0 (0.040)	60.0	----	47.0	6-7

[a]Depth below surface at which Rockwell C 50 occurs.

TABLE 5. - LUBRICANT PROPERTIES

Property	Synthetic paraffinic oil plus additives[b]	Diester plus TMP[a] polyester plus additives[c]
Kinematic viscosity, cm^2/sec (cs) at:		
244 K (-20° F)	2500×10^{-2} (2500)	580×10^{-2} (580)
311 K (100° F)	31.6×10^{-2} (31.6)	14.8×10^{-2} (14.8)
372 K (210° F)	3.7×10^{-2} (5.7)	3.7×10^{-2} (3.7)
477 K (400° F)	2.0×10^{-2} (2.0)	1.2×10^{-2} (1.2)
Flash point, K (°F)	508 (455)	491 (425)
Fire point, K (°F)	533 (500)	527 (490)
Pour point, K (°F)	219 (-65)	213 (-75)
Specific gravity	0.8285	0.950
Vapor pressure at 311 K (100° F), mm Hg (or torr)	0.1	10^{-5}
Specific heat at 311 K (100° F), J/(kg)(K) (Btu/(lb)(°F))	676 (0.523)	608 (0.470)

[a]Trimethylol propane.
[b]Additive, Lubrizol 5002 (5 percent volume): phosphorus, 0.03 percent volume, sulfur, 0.93 percent volume.
[c]Additive content is proprietary to the manufacture.

TABLE 6. - SPUR GEAR FATIGUE LIFE RESULTS

[Pitch diameter, 8.89 cm (3.5 in.); maximum Hertz stress, 1.71×10^9 N/m^2 (248 000 psi); speed, 10 000 rpm; lubricant, synthetic paraffinic oil; gear temperature, 350 K (170° F).]

Material	Heat treat procedure (see table 3)	Gear system life revolutions		Weibull slope	Failure index (a)	Confidence number (b)
		10-Percent life	50-Percent life			
AISI 9310	------	23×10^6	52×10^6	2.3	30 out of 30	--
Modified Vasco X-2	Lot D	38.4×10^6	253×10^6	1.0	12 out of 26	80
	Lot B	0.8×10^6	27.6×10^6	0.53	18 out of 21	99
	Lot C	3.3×10^6	8×10^6	2.1	19 out of 19	99
CBS 600	------	160×10^6 (estimated)	370×10^6 (estimated)	2.3	2 out of 20	99

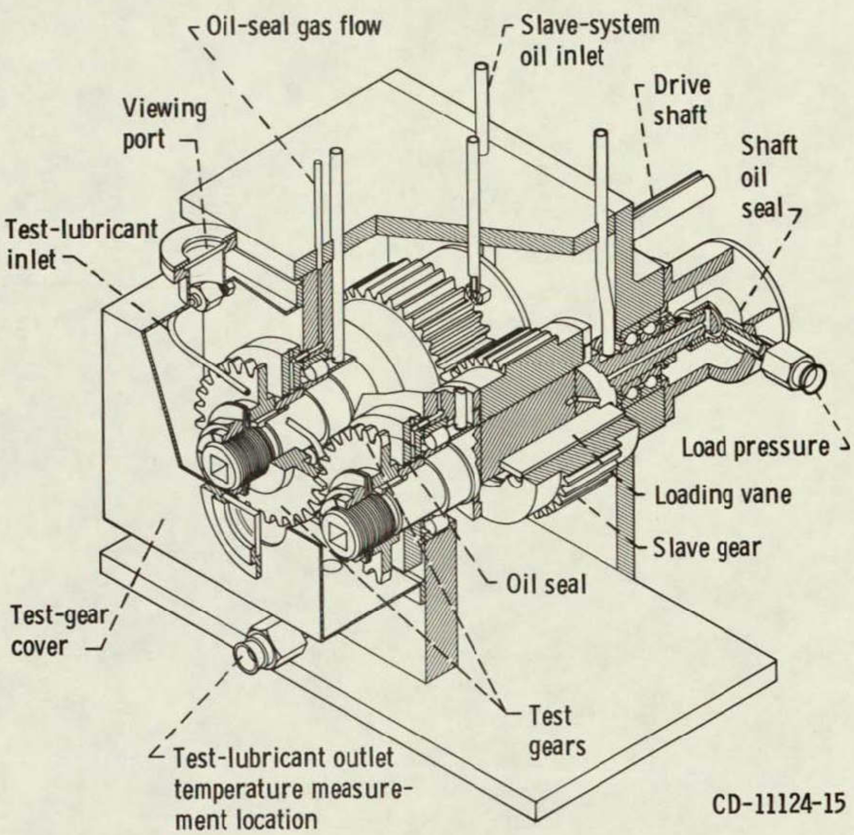
[a]Number of surface fatigue failures out of number of gears tested.
[b]Percentage of time that 10-percent life obtained with AISI 9310 gears will have the same relation to the 10-percent life obtained with modified Vasco X-2 gears or CBS 600.

TABLE 7. - FATIGUE-LIFE RESULTS IN ROLLING-CONTACT (RC) TESTER

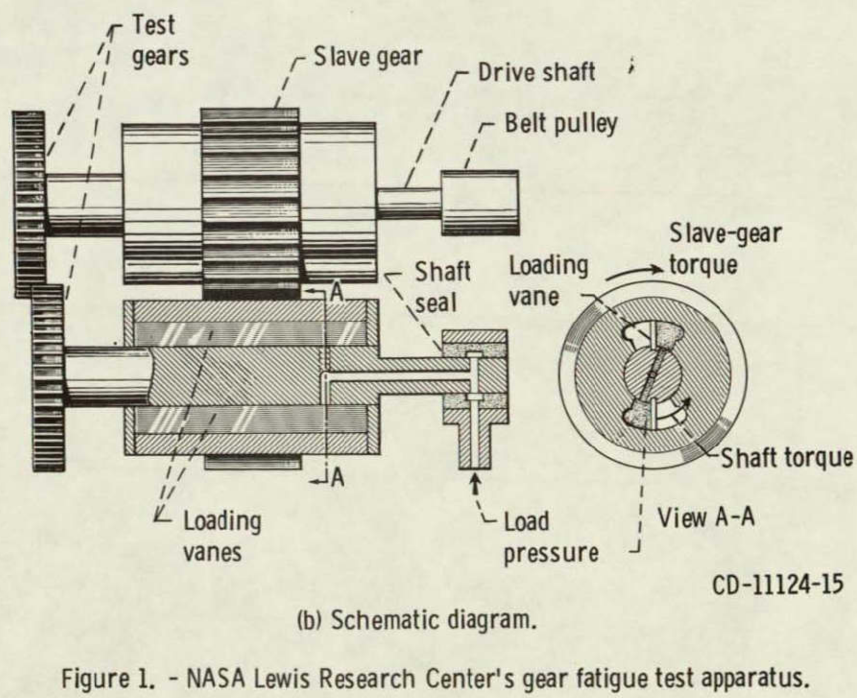
[Speed, 25 000 stress cycles per minute; maximum Hertz stress, 4.83×10^9 N/m^2 (700 000 psi); lubricant, MIL-L-7808, temperature, ambient.]

Material	Life, millions of stress cycles		Weibull slope	Failure index (a)	Confidence number at 10-percent life level (b)
	10-Percent life	50-Percent life			
Modified Vasco X-2	6.3	14.8	2.2	20 out of 20	75
CBS 600:					
Lot-					
A	1.9	7.3	1.4	10 out of 10	83
B	5.2	11.8	2.3	8 out of 10	60
C	5.8	11.0	3.0	10 out of 10	70
D	3.8	9.6	2.0	10 out of 10	55
AISI 9310	4.2	9.4	2.3	10 out of 10	--

[a]Number of failures out of number of tests.
[b]Percentage of time that 10-percent life obtained with AISI 9310 bars will have the same relation to the 10-percent life obtained with modified Vasco X-2 or CBS 600 bars.



(a) Cutaway view.



(b) Schematic diagram.

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

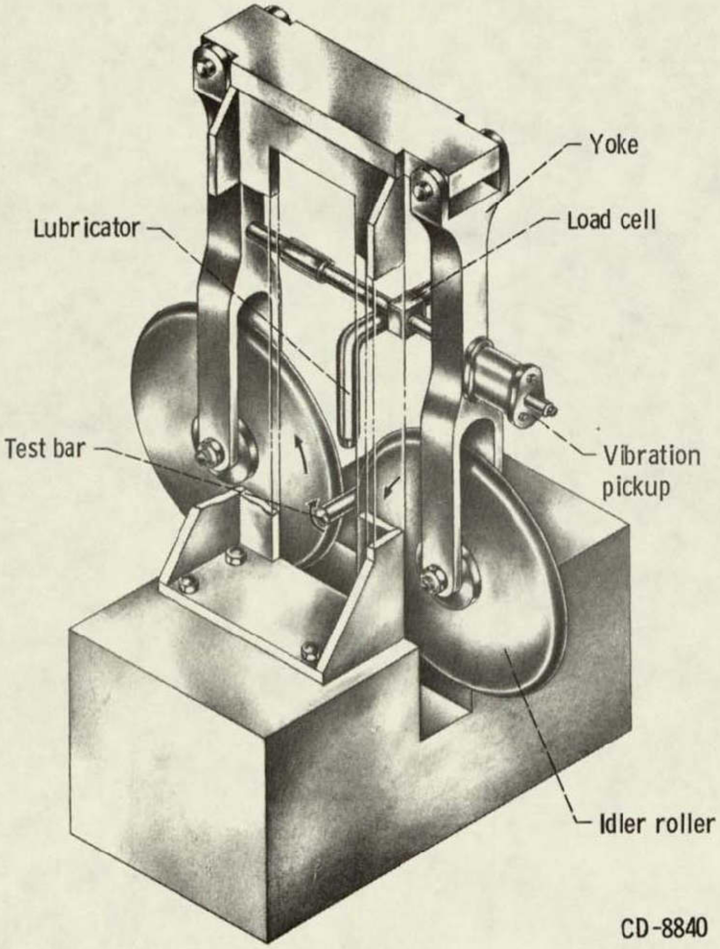


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Figure 2. - Rolling-contact (RC) fatigue tester.

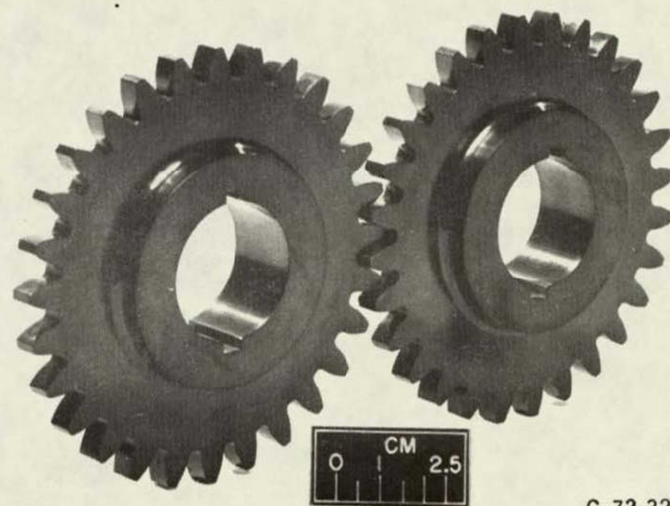

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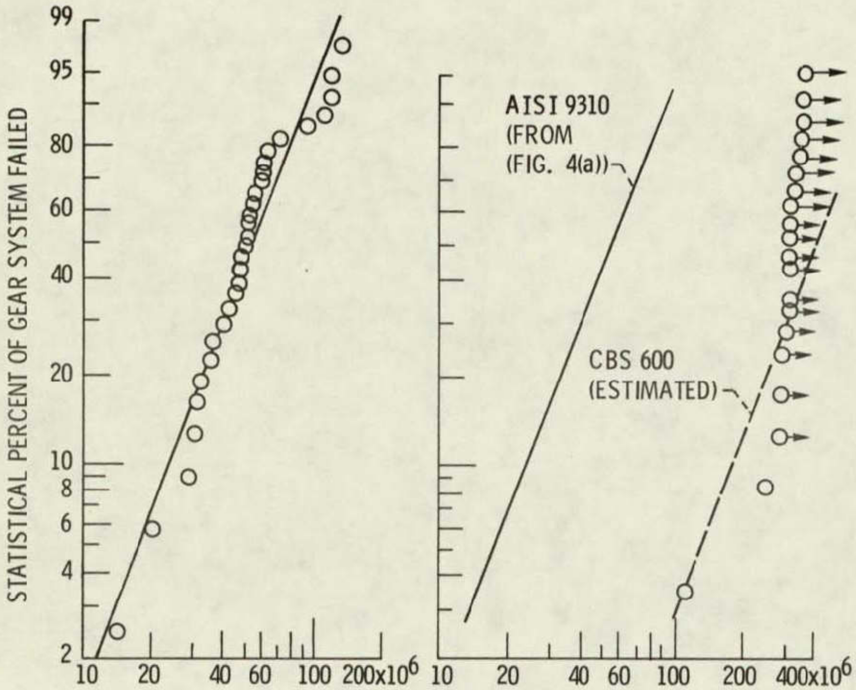
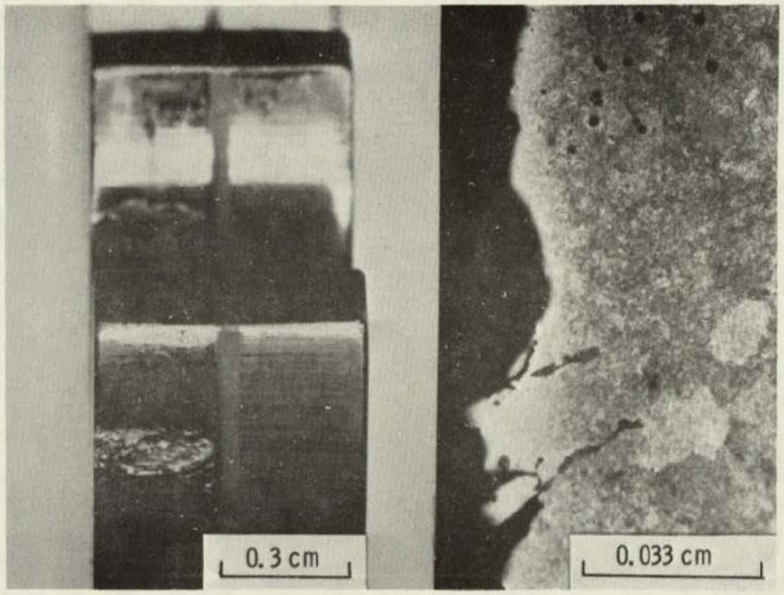
Figure 3. - Test-gear configuration.



(a) CVM AISI 9310.

(b) AIR-MELT CBS 600.

Figure 4. - Surface fatigue life of test gears. Speed, 10 000 rpm; maximum Hertz stress, 1.71×10^9 newtons per square meter (248 000 psi); temperature, 350 K (170^0 F); lubricant, synthetic paraffinic with 5 percent EP additive.



(a) FATIGUE SPALL.

(b) CROSS SECTION OF SPALL.

Figure 5. - Representative fatigue spall of test gear material CVM AISI 9310 steel. Speed, 10 000 rpm; lubricant, synthetic paraffinic oil with additive package.

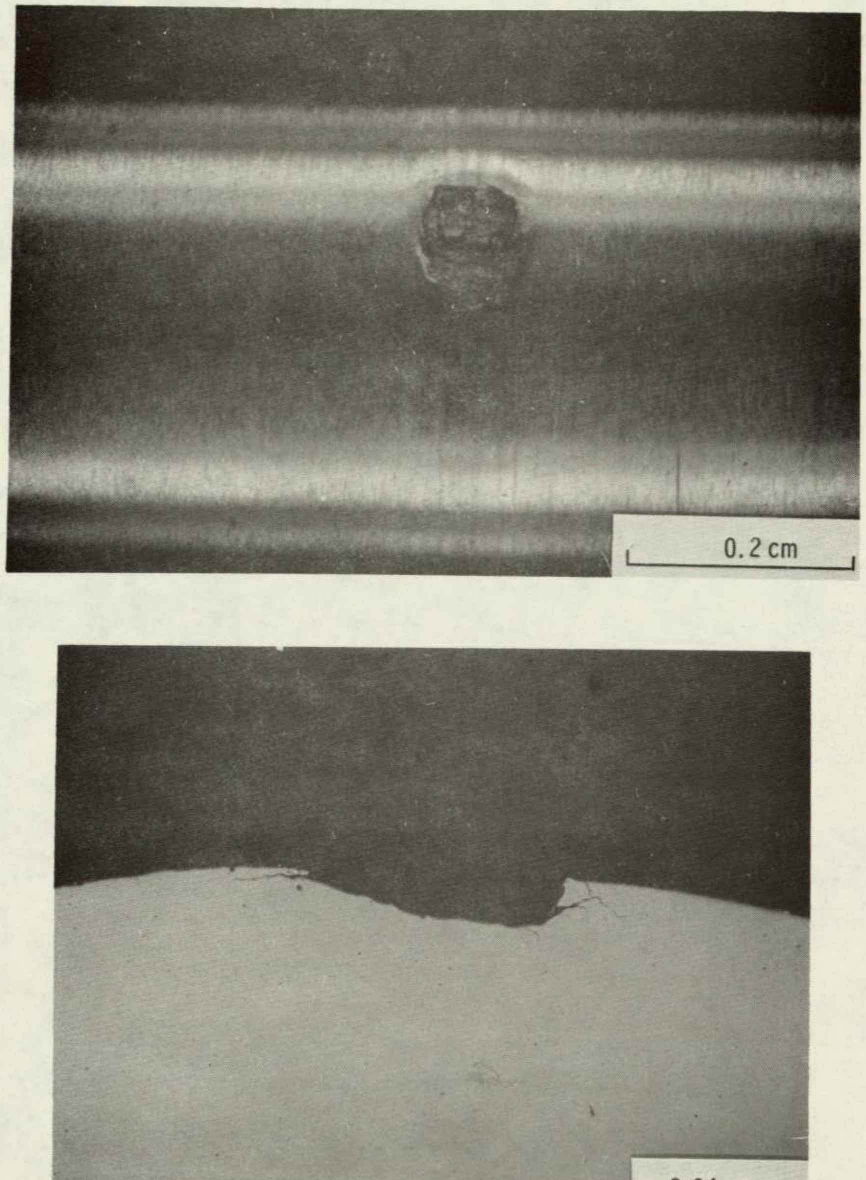
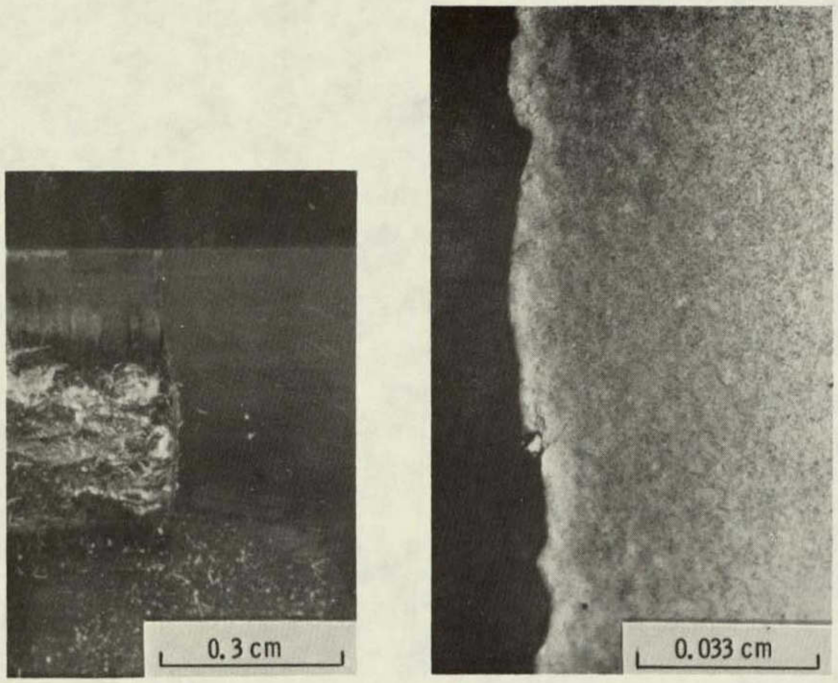


Figure 6. - Typical rolling-element fatigue failure in CBS 600.



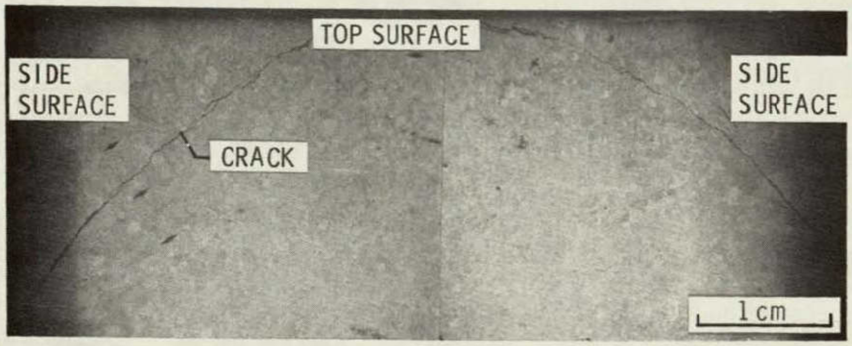
(a) FATIGUE SPALL.

(b) CROSS SECTION OF SPALL.

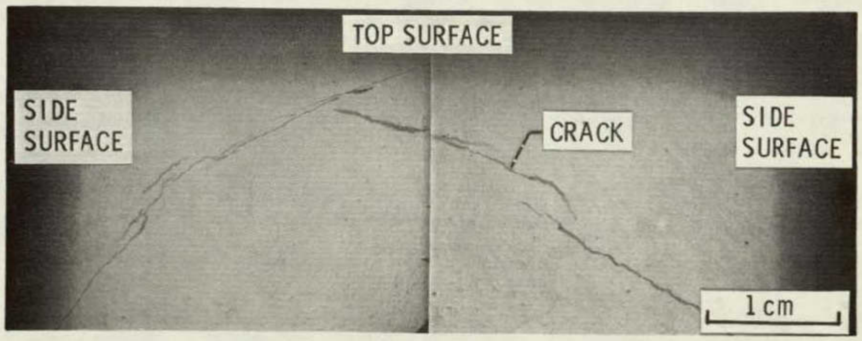
Figure 7. - Typical pitch-line fatigue spall of CBS 600 test gear. Speed, 10 000 rpm; lubricant, synthetic paraffinic oil with additive package.

Figure 8. - Typical tooth bending fracture on CBS 600 after running with a fatigue spall; speed, 10 000 rpm; lubricant, synthetic paraffinic oil with additive package.

Figure 9. - Typical fracture of modified Vasco X-2 gear teeth with NASA specified heat treatment carburized on all sides.



(a) CROSS SECTION OF UNFAILED GEAR TOOTH FROM FAILED MODIFIED VASCO X-2 GEAR SHOWING CRACK AT EACH CORNER OF TOOTH.



(b) CROSS SECTION OF GEAR TOOTH FROM UNRUN MODIFIED VASCO X-2 GEAR SHOWING CRACK.

Figure 10. - Cross section of unfailed and unrun modified Vasco X-2 gear teeth heat treated to NASA specification and carburized on all sides.

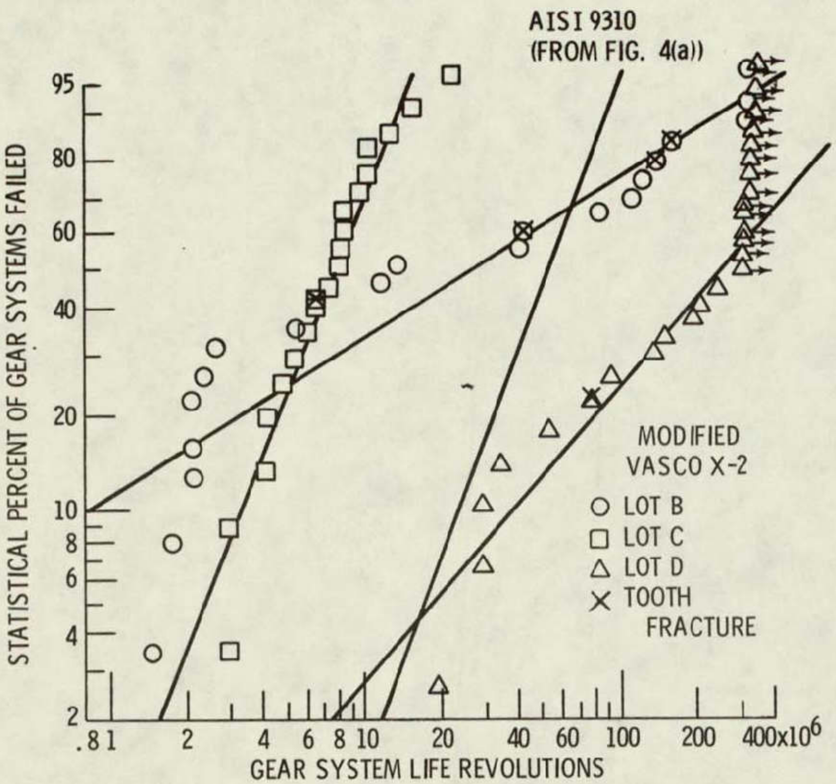


Figure 11. - Surface pitting fatigue lives of CVM modified VASCO X-2 spur gears heat treated to different specifications. Pitch diameter, 8.89 cm (3.5 in.); speed, 10 000 rpm; lubricant synthetic paraffinic oil; maximum Hertz stress, 1.71×10^9 N/m^2 (248 000 psi).

Figure 12. - Gear tooth fracture through a fatigue spall of NASA heat treated modified Vasco X-2, maximum Hertz stress, 1.71×10^9 N/m^2 (248 000 psi) speed, 10 000 rpm.

25

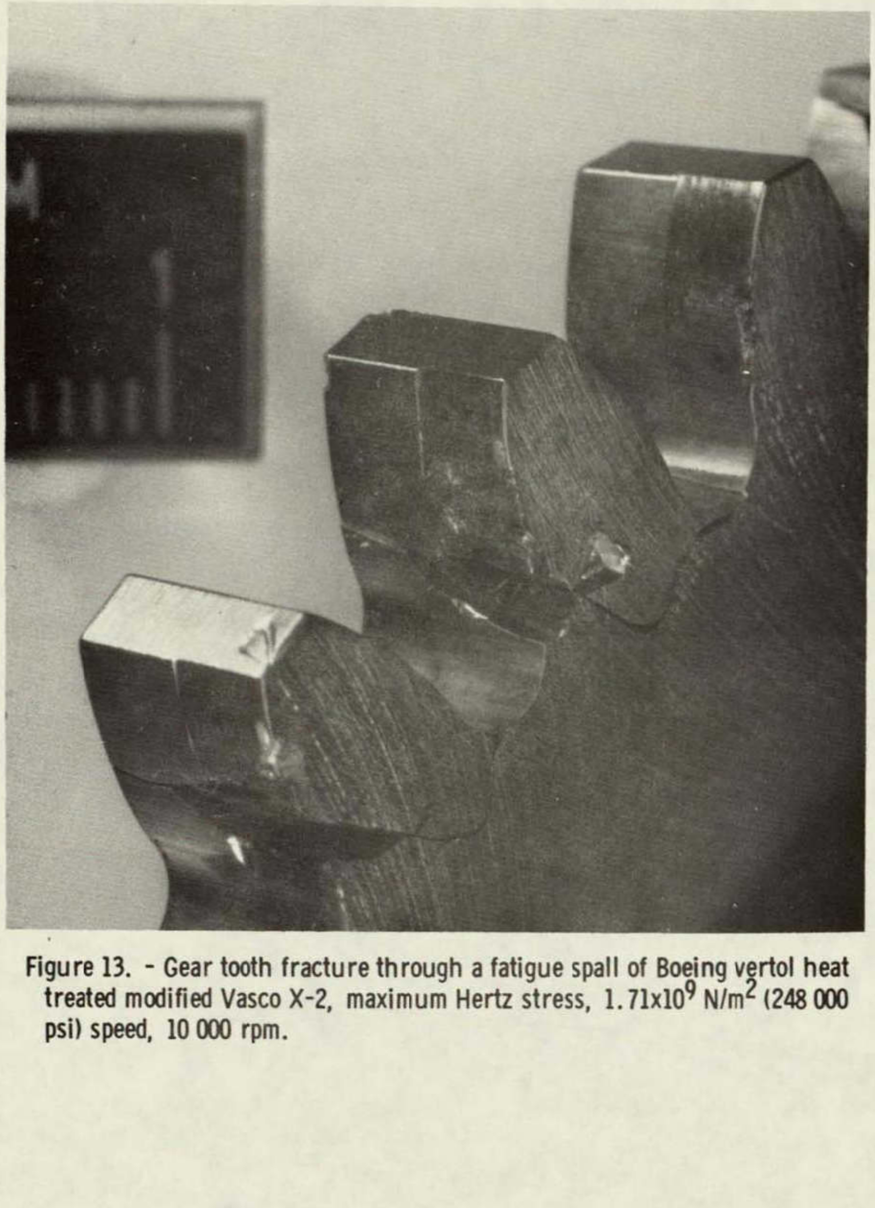


Figure 13. - Gear tooth fracture through a fatigue spall of Boeing vertol heat treated modified Vasco X-2, maximum Hertz stress, 1.71×10^9 N/m^2 (248 000 psi) speed, 10 000 rpm.

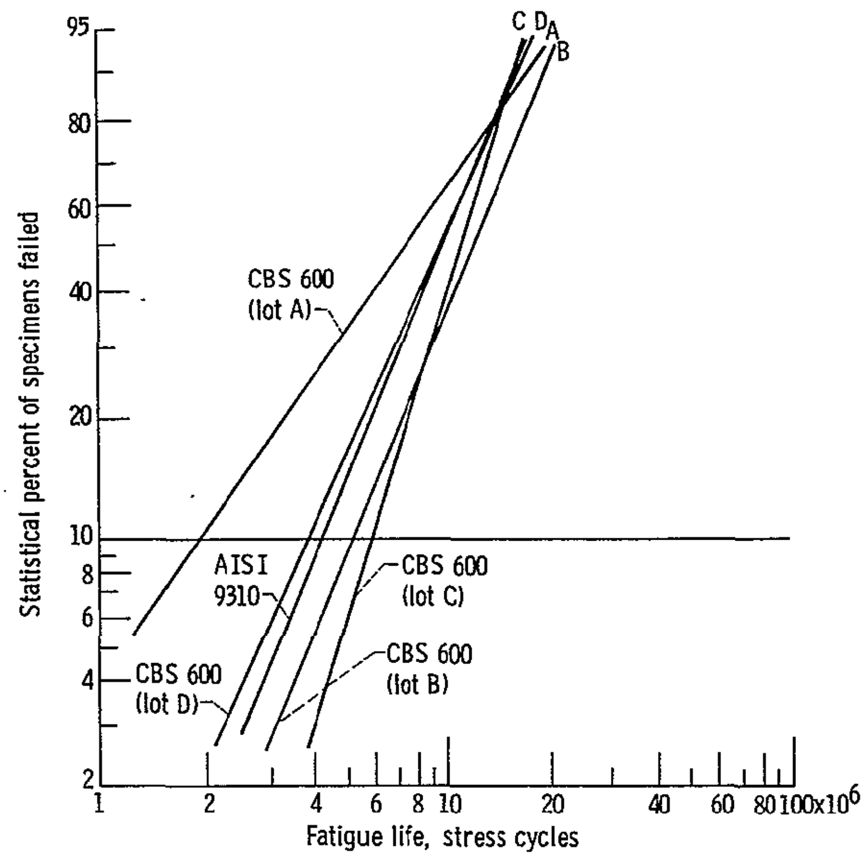


Figure 14. - Summary of rolling-element fatigue life data with CBS 600 and CVM AISI 9310 in rolling-contact fatigue tested (data from [7]).

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