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Comparisons of Modified VASCO X-2 and AISI 9310 Gear Steels

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Summary

Endurance tests were conducted with four groups of spur gears manufactured from three heats of consumable electrode vacuum melted (CVM) modified Vasco X-2. Each heat was subjected to a different heat treatment procedure. Additional endurance tests were conducted with spur gears which were manufactured from a single heat of CVM AISI 9310 steel. Test conditions for the gears included a gear temperature of 350 K (170° F), a maximum Hertz stress of 1.71×10^9 N/m² (248 ksi) and a speed of 10 000 rpm.

Bench type rolling-element fatigue tests were also conducted to compare the rolling-element fatigue life of modified Vasco X-2 material with AISI 9310. Test conditions were a speed of 12 500 rpm and a maximum Hertz stress of 4.83×10^9 N/m² (700 ksi).

Hardness measurements were made as a function of temperature to temperatures of 811 K (1000° F) for material samples of the modified Vasco X-2 and the AISI 9310.

The differences in life between the long lived gears manufactured from modified Vasco X-2 and the AISI 9310 gears was not statistically significant. These results were the same as those obtained with the rolling-element fatigue tests. Variations in lives between the different heats of the modified Vasco X-2 and heat treatment procedures can be primarily attributed to heat treatment quality control and resultant case hardness. The higher the case hardness the longer the life. At temperatures to approximately 422 K (300° F) there was no significant difference in hot hardness between the modified Vasco X-2 and the AISI 9310 materials.

Case carburization of all of the gear surfaces for the modified Vasco X-2 gears results in fracture of the gears. However, carburization of the gear flanks only, using a carefully controlled heat treatment procedure, eliminates this failure mode. Nevertheless, a surface fatigue spall on the tooth surface of a modified Vasco X-2 gear can act as a nucleus of a tooth fracture failure.

Introduction

Advanced aircraft and helicopter requirements are continually increasing the need for improved transmission gear materials. The improved materials

should have increased load carrying capacity and life in addition to increased temperature capability over those materials currently being used.

One material that has shown promise for advanced helicopter transmission systems is a material designated as modified Vasco X-2 (ref. 1). 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 core material would have a fracture toughness that is typically required of a good gear material.

The manufacturer of the Vasco X-2 material developed a recommended heat treatment specified in reference 2. The Curtis-Wright Corporation experimented with the Vasco X-2 as a possible gear material and developed the lower carbon modified Vasco X-2 with their heat treatment method for gear applications (ref. 3). The Boeing Vertol Company later developed their own heat treatment process which included a preoxidation process to prevent spotty carburization of the surface caused by the presence of chromium oxide (refs. 4 and 5). The material with the Boeing Vertol heat treatment was used in the U.S. Army Heavy Lift Helicopter Program (ref. 1), the Boeing UTAS Program (ref. 6) and the Boeing YHC-47D Program (ref. 7).

The objectives of the research reported herein were to (1) determine the performance of spur gears made from modified Vasco X-2 and heat treated by three different methods, (2) compare the surface pitting fatigue lives of the three heat treatments of modified Vasco X-2 with AISI 9310, and (3) compare hot hardness retention of Vasco X-2 with AISI 9310. In order to accomplish these objectives, tests were conducted with four groups of spur gears having three different heat treatments and manufactured from three heats of consumable electrode vacuum melted (CVM) modified Vasco X-2. One group of spur gears manufactured from a single heat of CVM AISI 9310 was also tested for comparison purposes. The gear pitch diameter was 8.89 centimeters (3.5 in.). Test conditions included a gear temperature of 350 K (170° F), maximum Hertz stresses of 1.71×10^9 N/m² (248 ksi), a speed of 10 000 rpm, and a synthetic

paraffinic lubricating oil. Bench type rolling-element fatigue tests were also conducted to compare one lot of the modified Vasco X-2 material with AISI 9310. Tests were conducted at a speed of 12 500 rpm, a maximum Hertz stress of 4.83×10^9 N/m² (700 ksi), and a MIL-L-7808-type lubricant was utilized. Hardness measurements were made at elevated temperatures on samples of AISI 9310 and modified Vasco X-2 materials.

Apparatus, Specimens, and Procedure

Rolling-Element Tests

Rolling-contact (RC) fatigue tester.—The rolling-contact (RC) fatigue tester is shown in figure 1. A cylindrical test bar is mounted in the precision chuck. A drive means is attached to the chuck thereby driving the bar which in turn drives two idler disks. The disks are 19 centimeters (7.5 in.) in diameter and have a crown radius of 0.635 centimeter (0.25 in.). The 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 system using a needle valve to control the flow rate. Several test runs can be made on one test bar by mov-

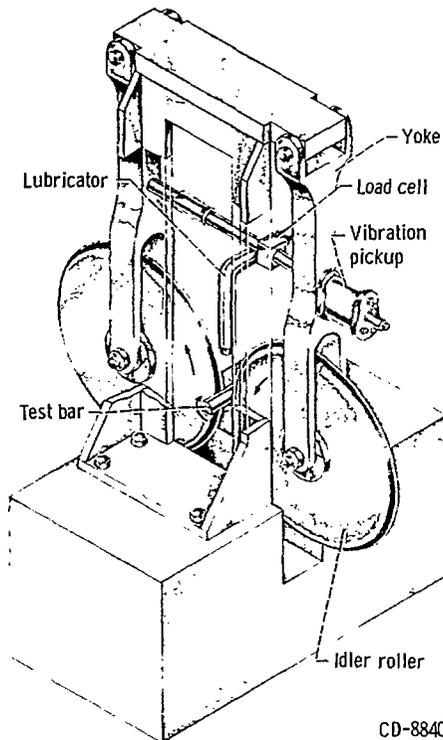


Figure 1. - Rolling-contact fatigue apparatus.

ing the bar position in the axial direction relative to disk contacts. The test bar is rotated at 12 500 rpm thus receiving 25 000 stress cycles per minute. The maximum Hertz stress was 4.83×10^9 N/m² (700 ksi). This condition produces subsurface fatigue spalls (ref. 8).

The rolling-element fatigue tests with the RC bar specimens of both materials were lubricated with a MIL-L-7808 type lubricant. The fluid comprised a mixture of two base stocks, a diester plus a TMP polyester. The additives in this fluid included antioxidants, load-carrying additives, metal passivators, hydrolytic stability additive, and a silicone antifoam additive. The types and levels of the additives were proprietary. The physical properties of this lubricant are summarized in table I.

Test bar specimens.—The 7.62-centimeter (3-in.) long cylindrical test bars for fatigue tests were fabricated from modified Vasco X-2 and AISI 9310 as described in table II. The test bars were heat treated to NASA specifications as given in table III. The heat treatment for the Vasco X-2 test bars is

TABLE I. - 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)	5.7×10 ⁻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/(g)(K) (Btu (lb)(°F))	676 (0.523)	608 (0.470)

^aTrimethylol propane

^bAdditive, Lubrizol 5002 (5 percent volume); phosphorus, 0.03 percent volume; sulfur, 0.93 percent volume.

^cAdditive content is proprietary to the manufacturer.

TABLE II. - CERTIFIED CHEMICAL COMPOSITION OF TEST MATERIALS BY PERCENT WEIGHT

Element	AISI 9310		Modified Vasco X-2		
	Gears	RC specimens	NASA ^a	Curtis-Wright	Boeing Vertol
Carbon (core)	0.10	0.09	0.12	0.14	0.15
Manganese	.63	.66	.29	.24	.25
Phosphorous	.005	.012	.012	.011	.015
Sulfur	.005	.005	.008	.011	.002
Silicon	.37	.23	.88	.95	.87
Copper	.13	.10	.09	.06	----
Chromium	1.21	1.36	4.95	4.76	4.94
Molybdenum	.12	.15	1.34	1.4	1.35
Vanadium	----	----	.42	.45	.40
Nickel	3.22	3.16	.06	.10	----
Cobalt	----	----	.02	.03	----
Tungsten	----	----	1.32	1.40	1.35
Iron	Balance	Balance	Balance	Balance	Balance

^aSame as for RC test specimens.

TABLE III. - HEAT TREATMENT

Step	Process	AISI 9310				Modified Vasco X-2											
		Treated	K	°F	hr	Boeing Vertol X-2				NASA X-2				Curtis-Wright X-2			
						Treated	K	°F	hr	Treated	K	°F	hr	Treated	K	°F	hr
1	Rough machine	Yes	---	---	---	Yes	---	---	---	Yes	---	---	---	Yes	---	---	---
2	Preclean blast of aluminum oxide	No	---	---	---	Yes	---	---	---	No	---	---	---	No	---	---	---
3	Preheat in air	No	---	---	---	No	---	---	---	---	---	---	---	---	---	---	---
4	Preoxidat at temperature	No	---	---	---	---	1255	1800	0.75	---	1283	1850	0.5	No	---	---	---
5	Air cool	No	---	---	---	---	---	---	---	Yes	---	---	---	No	---	---	---
6	Copper plate area not carburized	Yes	---	---	---	Yes	---	---	---	Yes	---	---	---	Yes	---	---	---
7	Carburize 0.85 - 1.00% carbon potential	Yes	1172	1650	---	Yes	1200	1700	6	---	1200	1700	---	---	1200	1700	1.75
8	Furnace cool to	No	---	---	---	---	1090	1500	---	No	---	---	---	---	---	1061	1450
9	Air cool	Yes	---	---	---	Yes	---	---	---	Yes	---	---	---	Oil quench	---	---	---
10	Stress relieve	Yes	922	1200	2.5	---	589	600	2	No	---	---	---	---	---	422	300
11	Strip copper plate	Yes	---	---	---	Yes	---	---	---	Yes	---	---	---	Yes	---	---	---
12	Blast clean aluminum oxide	No	---	---	---	Yes	---	---	---	No	---	---	---	No	---	---	---
13	Nickel plate (0.0003 mas)	No	---	---	---	Yes	---	---	---	No	---	---	---	No	---	---	---
14	Copper plate (0.001 min)	Yes	---	---	---	Yes	---	---	---	No	---	---	---	No	---	---	---
15	Preheat	No	---	---	---	---	1061	1450	0.5	No	---	---	---	---	---	1090	1500
16	Austenitize	---	1117	1550	2.5	---	1263	1850	0.5	---	1283	1850	1	---	---	1283	1850
17	Oil quench	Yes	---	---	---	Yes	---	---	---	Yes	---	---	---	Yes	---	---	---
18	Deep freeze	---	189	-120	3.5	---	200	-100	3	---	200	-100	3	No	---	---	---
19	Double temper	---	422	300	2 (each)	---	589	600	2 (each)	---	589	600	2 (each)	---	---	589	600
20	Blast clean aluminum oxide	No	---	---	---	Yes	---	---	---	No	---	---	---	No	---	---	---
21	Strip copper plate	Yes	---	---	---	Yes	---	---	---	No	---	---	---	No	---	---	---
22	Finish grind	Yes	---	---	---	Yes	---	---	---	No	---	---	---	Yes	---	---	---

similar to Boeing Vertol specification. The certified chemical composition for this heat of Vasco X-2 material is given in table II. The case and core hardnesses were Rockwell C 60 to 63 and Rockwell C 46, respectively. The contacting disks were machined from a fourth heat of CVM AISI M-50 steel and heat-treated to the same hardness as the bars. The test bars were ground to a diameter of 0.95 centimeter (0.375 in.) with a surface finish of 0.13 to 0.2 micrometer (5 to 8 μin.) CLA. Similarly, the disks were ground to a disk diameter of 19 centimeters (7½ in.) and a crown radius of 0.635 centimeter (0.25 in.). The surface finish of the disks was the same as that of the test bars.

Test procedure.—Rolling-element fatigue testing was performed in the RC rig. The test bar was installed and the disks were brought against the bar using a turnbuckle. A load was applied sufficient to allow the bar to drive the contacting disks, and the bar was accelerated to the desired speed. No external heat was added to the test system.

When the disks and test bar were in thermal equilibrium, the full load was applied. When a fatigue failure occurred, the rig and related instrumentation were automatically shut down. The axial position of the test bar in the drive chuck was changed in order to use a new running track, and testing was resumed.

Hardness Measurements

Test specimens.—Specimens approximately 0.76 centimeter (0.300 in.) thick and 3.81 centimeters (1.5 in.) in diameter or 3.81 centimeters (1.5 in.) square were carburized and hardened to the NASA specifications and tempered at 811 K (1000° F) so

that a uniform case was formed on all surfaces of the specimen (refs. 9 and 10). A test surface free of the massive carbides that occur during heat treatments was formed by grinding 0.038 centimeter (0.015 in.) of material from the hardened surface. One specimen was sectioned into smaller pieces with a cutoff wheel. A copious supply of coolant was supplied during this operation to prevent specimen overheating. One of these smaller specimens was used to measure the hardness of the case as shown in figure 2.

Another specimen was used to determine the hardness gradient of the material. The hardness gradient was established from a series of Knoop hardness measurements made across a section at the center of the specimen. The results of these measurements are shown in figure 2 as Rockwell C equivalents converted from Knoop hardness numbers as a function of depth below the specimen surface.

The core of the specimen was defined to be the region of minimum hardness shown in figure 2. With the hardness gradient established, material was ground from another of the sectioned samples until the core surface was exposed.

Apparatus and procedure.—Elevated temperature hardness measurements were made with a motorized Rockwell hardness tester fitted with an electric resistance furnace (shown in fig. 3). Errors due to major load dwell time were minimized by the automatic cycling operations of the motorized tester. A nitrogen cover gas was used within the furnace to inhibit surface oxidation and decarburization of the test specimens. A large size dial indicator was fitted to the tester so that readings to the nearest tenth of a point Rockwell "A" could be made.

All elevated temperature hardness measurements were made using the Rockwell "A" scale, 60

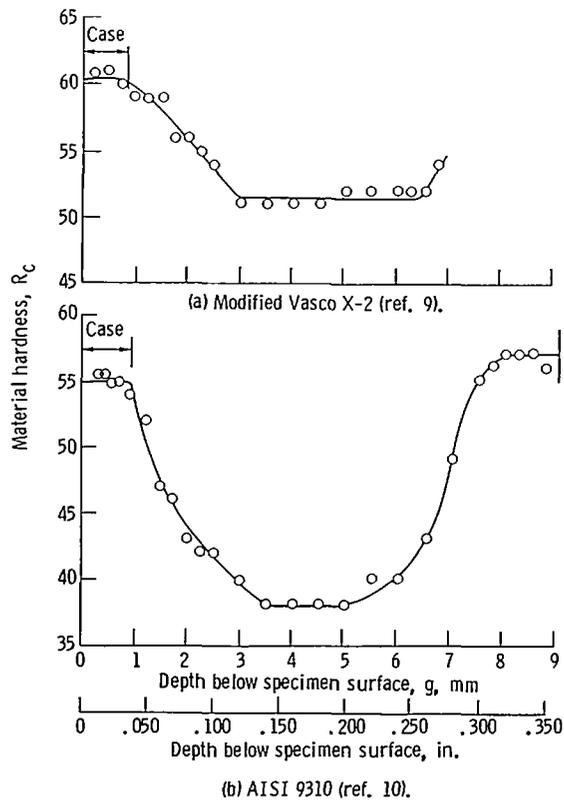


Figure 2. - Microhardness gradient (room temperature Knoop hardness measurements converted to Rockwell C equivalents).

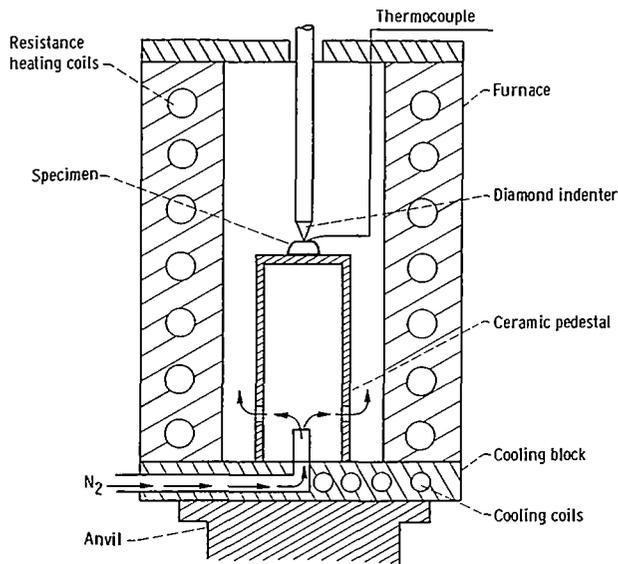


Figure 3. - Cross section of hot-hardness tester.

kilogram weight, with a Rockwell C diamond indenter. These measurements were converted to their Rockwell C equivalents. Use of the Rockwell "A" scale for testing case hardened materials is necessary to minimize indenter depth of penetration. Maximum indenter penetration was 0.076 millimeter (0.003 in.) in the case and 0.1 millimeter (0.004 in.) in the core. Standard testing procedure required homogeneous material below the tested surface to a depth of 10 times the indenter penetration depth (ref. 11). All specimens tested met this requirement.

Specimen temperatures were measured by means of a thermocouple welded to the surface of the specimens. The specimens were stabilized for approximately 15 minutes at the test temperature before any measurements were taken. A minimum of three hardness measurements were made at each temperature.

Gear Tests

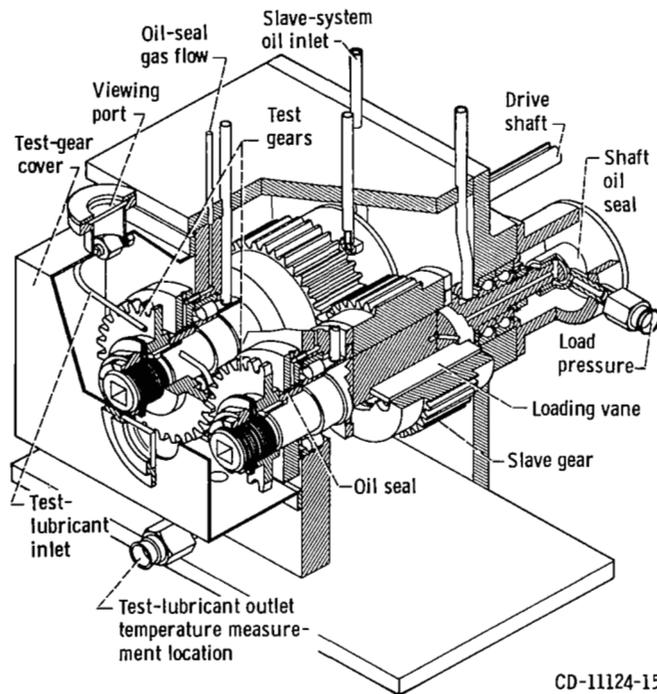
The gear fatigue tests were performed in the NASA Lewis Research Center's gear test apparatus (fig. 4). This test rig uses the four-square principle of applying the test gear load so that the input drive need only overcome the frictional losses in the system.

A schematic of the test rig is shown in figure 4(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.

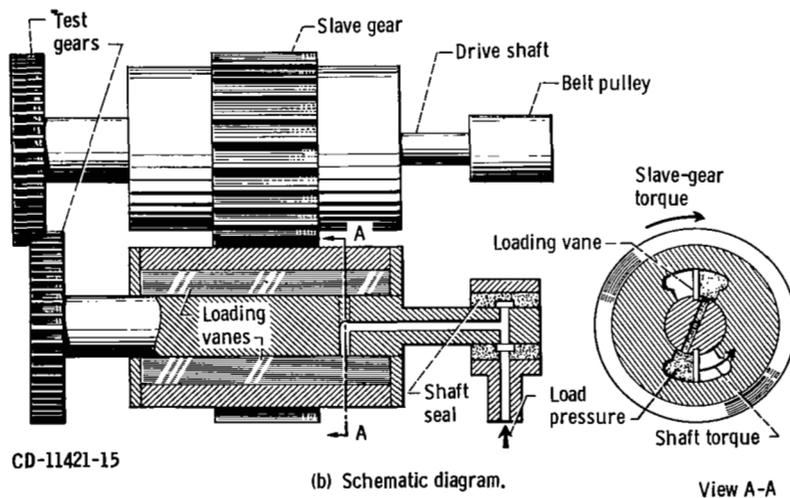
Separate lubrication systems are provided for the test gears and the main gearbox. The two lubricant systems are separated at the gearbox shafts by pressurized labyrinth seals. Nitrogen was the seal gas. The test gear lubricant is filtered through a 5-micron nominal fiberglass filter.

A vibration transducer mounted on the gearbox was used to automatically shut off the test rig when gear-surface fatigue occurs. The gearbox was 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.

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



(a) Cutaway view.



(b) Schematic diagram.

Figure 4. - NASA Lewis Research Center's gear-fatigue test machine.

Lubrication was supplied to the inlet mesh of the gear set by jet lubrication. The lubricant was circulated through a 5-micron fiberglass filter to remove wear particles. A total of 3800 cubic centimeters (1 gal) of lubricant was used for each test and was discarded, along with the filter element, after each test. Inlet and outlet oil temperatures were continuously recorded on a strip-chart recorder.

Lubricant flow rate was held constant at 800 cubic centimeters per minute. The lubricant inlet temperature was constant at 319 ± 6 K ($115 \pm 10^\circ$ F), and the lubricant outlet temperature was nearly constant at 350 ± 3 K ($170 \pm 5^\circ$ F). This outlet temperature was measured at the outlet of the test-gear cover. A nitrogen cover gas was used throughout the test as a baseline condition which

allowed testing at the same conditions at much higher temperatures without oil degradation. This cover gas by excluding oxygen also reduced the effect of the oil additives on the gear surface boundary lubrication by reducing the chemical reactivity of the additive-metal system (ref. 12).

The test gears were cleaned with solvent to remove the preservative and then assembled on the test rig. The test gears were run in an offset condition with a 3.05 millimeter (0.12 in.) tooth-surface overlap to give a load surface on the gear face of 28 mm (0.11 in.) of the 6.35 millimeter (0.250 in.) wide gear, thereby allowing for the edge radius of the gear teeth. By testing both faces of the gears, a total of four fatigue tests could be run for each set of gears. All tests were run-in at a normal load of 2714×10^2 N/m (1550 lb/in.) for 1 hour. The normal load was then increased to 616×10^2 N/m (3518 lb/in.) with a 1.71×10^9 N/m² (248 ksi) pitch-line Hertz stress. At the pitch-line load the tooth root bending stress was 0.226×10^9 N/m² (32.7 ksi) 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 root stress of 0.286×10^9 N/m² (41.5 ksi).

The test gears were operated at 10 000 rpm, which gives a pitch-line velocity of 2800 meters per minute (9163 ft/min). Lubricant was supplied to the inlet mesh at 800 cc per minute (0.21 gal/min) at 310 ± 6 K ($115 \pm 10^\circ$ F). The tests were run continuously 24 hours a day. Shut down was achieved automatically by means of a vibration-detection transducer located on the gearbox, adjacent to the test gears when vibration amplitude exceeded a preset value.

The pitch-line elastohydrodynamic (EHD) film thickness was calculated by the method of reference 13. 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 sliding contact. The EHD film thickness for these conditions was computed to be 0.33 micrometer (13 μ m.), which gave a ratio of film thickness to composite surface roughness h/σ of 0.55 at the 171×10^9 -N/m² (248-ksi) pitch-line Hertz stress.

Test Gears and Materials

Modified Vasco X-2.—Two groups of test gears (designated NASA in Table II) and the RC bar specimens were manufactured from a single material heat. The Curtis-Wright gears and the Boeing Vertol

gears were manufactured from two additional heats of modified Vasco X-2. The chemical composition for all three heats of material are given in table II.

Two groups of modified Vasco X-2 gears and the RC bar specimens were case carburized, hardened and tempered in accordance with the NASA heat-treatment specification given in table III. The gears were rough machined 0.38 millimeter (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 millimeter (0.028 in.). One group of these gears was carburized over all its surface while the second group of gears were carburized on the gear flanks only.

Figure 5(a) shows a cross section through a gear tooth showing the carburized case and core grain structure for these gears. The case hardness for these gears was Rockwell C (R_c) 57 and the core hardness was Rockwell C 47. Figures 5(b) and (c) provides an enlarged view of the case and core grain structure.

The Curtis-Wright gears were heat treated in accordance with the heat treat schedule given in table III. The one major difference in this heat treatment is the absence of the preoxidation treatment. A cross section of one of these gears is shown in figure 6(a). The case and core structure are shown in figures 6(b) and (c). The case hardness for these gears was Rockwell C 57 which is four points below the optimum of Rockwell C 61. The core hardness was Rockwell 47.

The Boeing Vertol gears were heat treated in strict accordance with the Boeing Vertol specifications and under the direction of the Boeing Vertol quality control personnel. This heat treatment is assumed to be according to the Boeing patent (refs. 4 and 5) and is given in table III. Approximately 0.030 centimeter (0.012 in.) were removed from the surface during the finishgrinding operation. Figure 7(a) shows a cross section of these gears showing the carburized case and core grain structure. The case hardness was Rockwell C 61 and the core hardness was Rockwell C 45. Figures 7(b) and (c) provide an enlarged view of the case and core grain structure. The case structure has a very fine dispersion of carbides showing no excess carbides and no coarse grain structure.

AISI 9310.—The AISI 9310 gears were manufactured from a single heat of consumable electrode vacuum melted (CVM) AISI 9310. The chemical composition of the AISI 9310 gears is given in table II. The heat treatment for the AISI 9310 gears is given in table III. A photomicrograph of etched and polished surface of the AISI 9310 gear is shown in figure 8. The case hardness of the gears was Rockwell C 59 to 61. The gear core hardness was Rockwell C 35 to 40.

Dimensions for the AISI 9310 test gears are given in table IV. All gears have a nominal surface finish

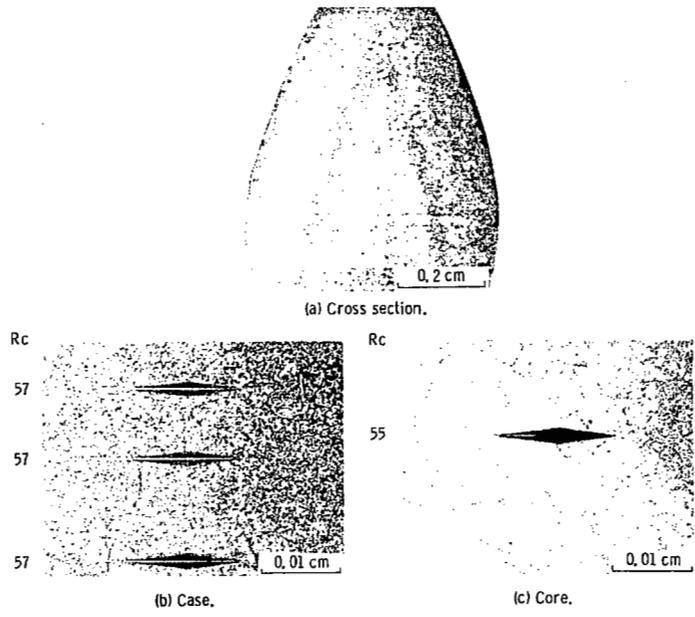


Figure 5. - Photomicrograph of treated modified Vasco X-2 gear with NASA specified heat treatment.

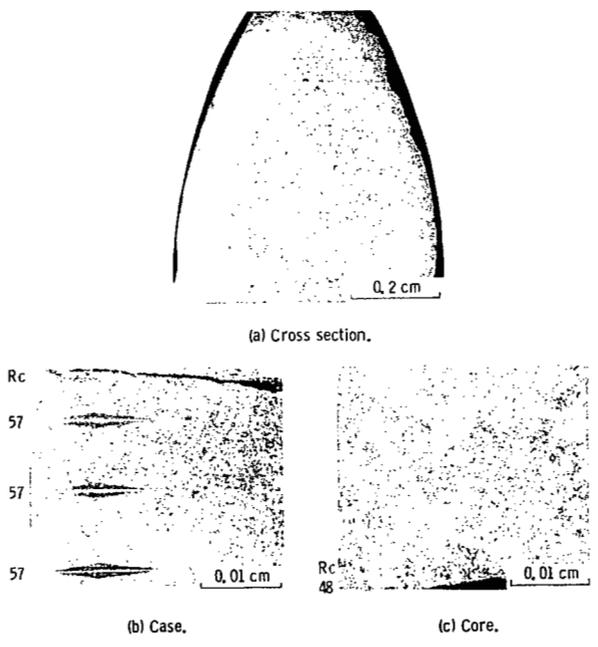


Figure 6. - Photomicrograph of modified Vasco X-2 gear with Curtis-Wright specified heat treatment.

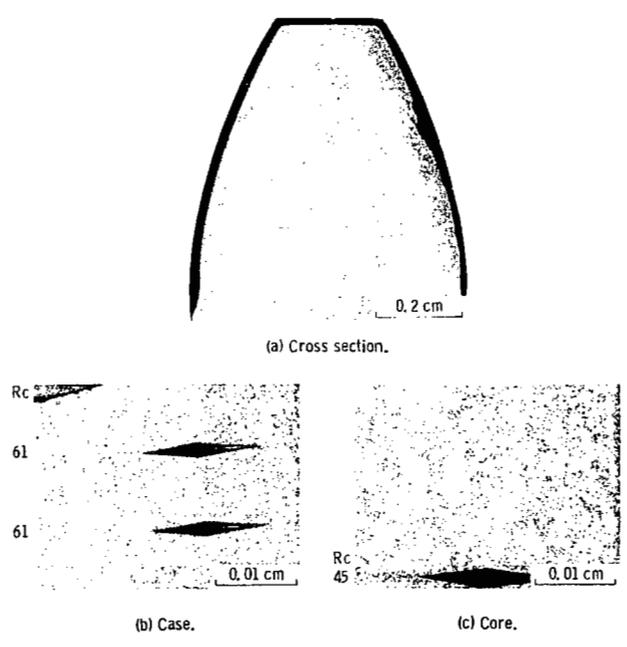
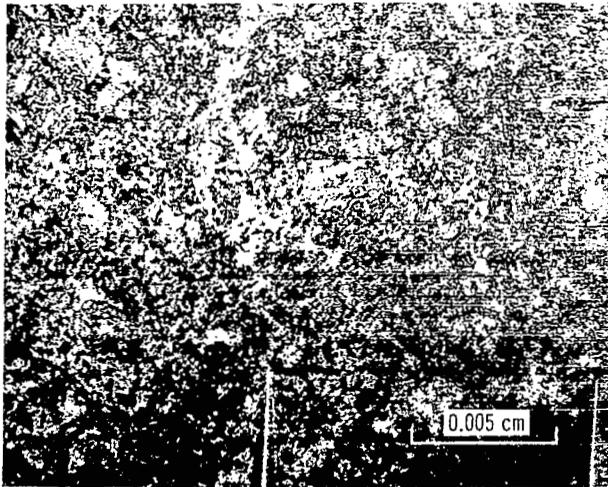
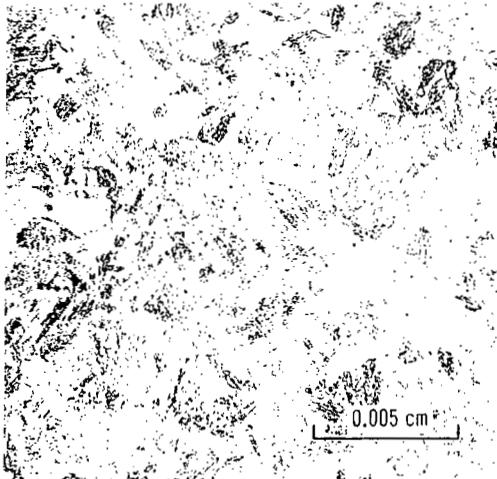


Figure 7. - Photomicrograph of modified Vasco X-2 gear with Boeing Vertol specified heat treatment.



(a) Carburized and hardened case of the AISI 9310 gear showing high carbon fine grain martensitic structure.



(b) Core structure of AISI 9310 gear showing low carbon refined austenitic grain size.

Figure 8. Photomicrographs of case and core regions of test gears.

TABLE IV. - 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)

on the tooth face of 0.406 micrometer (16 μ m.) rms and a standard 20° involute profile. The AISI 9310 and NASA modified Vasco X-2 gears and a tip relief of 0.013 millimeter (0.0005 in.) starting at the highest point of single tooth contact. The Boeing Vertol modified Vasco X-2 gears had a dedendum relief of 0.023 millimeter (0.0009 in.) with no tip relief. The Curtis Wright modified Vasco X-2 gears had no profile modification.

Results and Discussion

Hardness Retention

The ability of a material to retain its hardness at elevated temperature, in view of its direct influence on rolling-element fatigue life, is an important design criterion for high-performance gears and rolling-element bearings such as those found in helicopter transmissions. Apart from a potential reduction in fatigue life, low hardness of rolling-element bearing components can result in permanent surface deformation and distress during operation leading to premature failure.

Hot-hardness measurements were made on the case and core areas of modified Vasco X-2 and AISI 9310 (refs. 9 and 10). The results of these measurements are shown in figures 9(a) and 10(a) as plots of hardness against specimen temperature for each material. To eliminate room temperature hardness differences, the data of figures 9(a) and 10(a) were normalized in figures 9(b) and 10(b), respectively. Figures 9(b) and 10(b) are plots of the change in hardness from room temperature hardness as a function of specimen temperature. These data indicate the similarity between changes in case and core hardness with temperature.

The individual normalized short-term hot-hardness curves for the case from figures 9(b) and 10(b) are combined for comparison in figure 11. AISI 9310 experienced a relatively rapid decrease in material hardness with temperature. The modified Vasco X-2 had a more gradual decrease in material hardness with temperature up to 811 K (1000° F). These data are consistent with the tempering characteristics of these two steels. At temperatures to approximately 422 K (300° F) there was no significant difference in the decrease in hardness with temperature between the materials.

In figure 12 data for modified Vasco X-2 are compared with data from reference 14 for a large number of through hardened high-speed tool steels. Vasco X-2 similar to those tool steels in that it also is a precipitation hardening alloy. From figure 12 it is evident that the Vasco X-2 steel has hot-hardness characteristics similar to the through-hardened high-

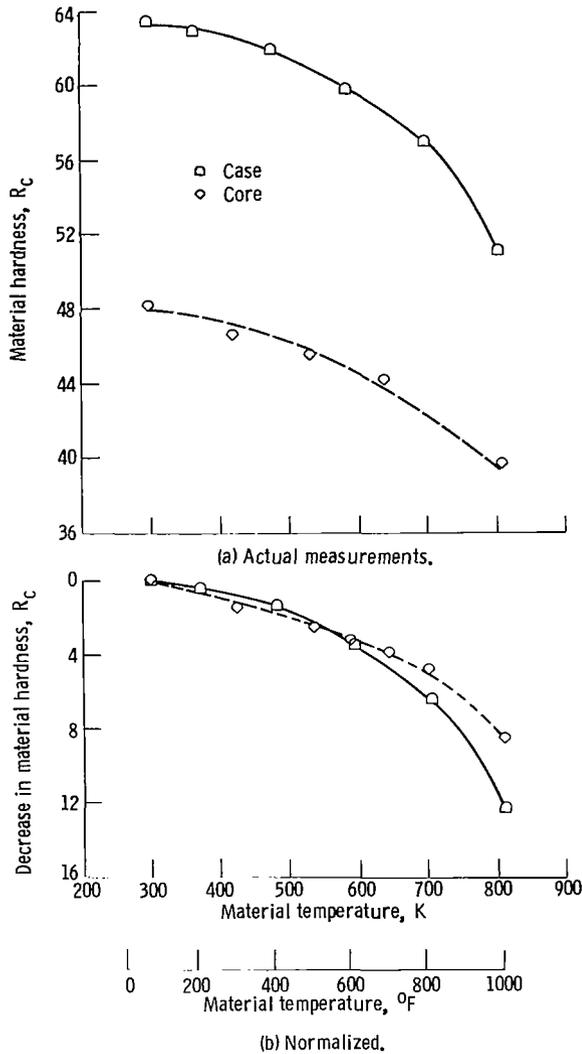


Figure 9. - Short-term hot-hardness characteristics of modified Vasco X-2 (ref. 9).

speed tool steels up to approximately 644 K (700° F). Above this temperature Vasco X-2 hardness decreases more rapidly. The changes in hardness as a function of temperature for Vasco X-2 and AISI 9310 satisfy the equation developed in reference 14 for the prediction of hardness with change in temperature

$$(Rc)_T = (Rc)_{RT} - \alpha \Delta T^\beta$$

where

- $(Rc)_T$ Rockwell C hardness at temperature
- $(Rc)_{RT}$ Rockwell C hardness at room temperature
- ΔT change in temperature, $T_T - T_{RT}$
- T_T operating temperature, K; °F

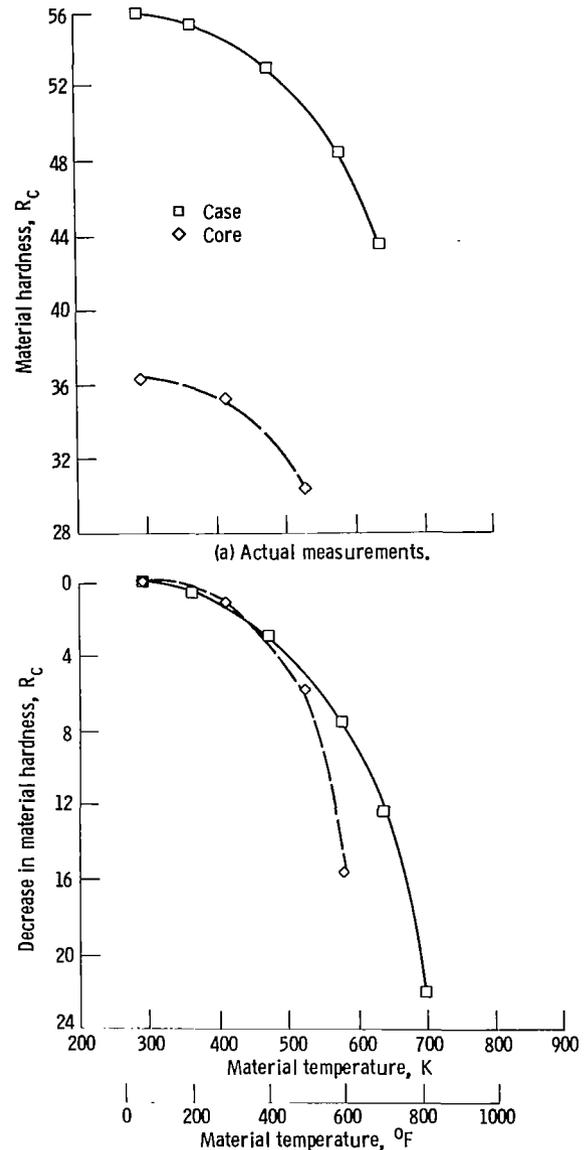


Figure 10. - Short term hot-hardness characteristics of AISI 9310 (ref. 10).

- T_{RT} room temperature, K; °F
- α temperature proportionality factor, $(K)^{-\beta}$; $(^\circ F)^{-\beta}$
- β exponent

The values for α and β modified Vasco X-2 and AISI 9310 are summarized in table V. The equation is valid for AISI 9310 from 298 to 589 K (70° to 600° F) and for modified Vasco X-2, from 294 to 811 K (70° to 1000° F).

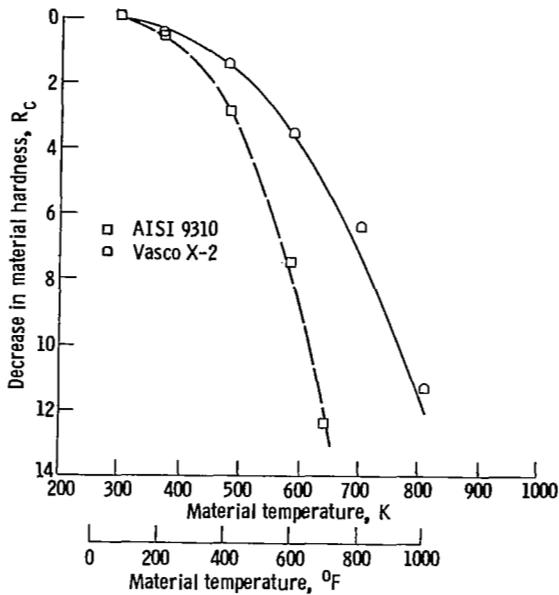


Figure 11. - Comparison of normalized short-term case hot-hardness characteristics of AISI 9310 and modified Vasco X-2 (ref. 10).

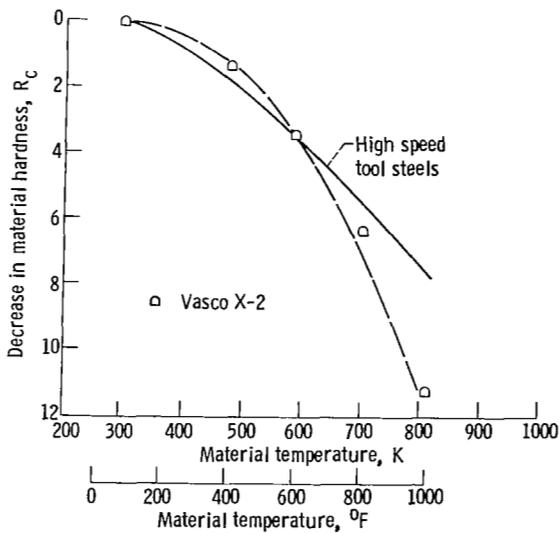


Figure 12. - Comparison of normalized short-term hot-hardness characteristics of modified Vasco X-2 and tool steels (ref. 9).

TABLE V. - TEMPERATURE PROPORTIONALITY FACTORS α AND EXPONENTS β
[$(Rc)_T = (Rc)_{RT} - \alpha \Delta T^\beta$.]

Material	Temperature range		α		β	
	K	°F	K	°F	K	°F
AISI 9310	294 to 589	70 to 600	1.92×10^{-5}	0.50×10^{-5}	2.3	2.3
Vasco X-2	294 to 811	70 to 1000	1.4×10^{-5}	0.38×10^{-5}	2.2	2.2

Rolling-Element Fatigue

Rolling-element fatigue tests were conducted with the modified Vasco X-2 heat treated to the NASA specifications shown in table VI and the AISI 9310 materials with a MIL-L-7808 lubricant (ref. 15). Test temperature was ambient room temperature, a maximum Hertz stress of 4.83×10^9 N/m² (700 psi) and a speed of 12 500 rpm or 25 000 stress cycles per minute. The results of these tests are shown in figure 12 and summarized in table VI. The data were analyzed using the methods of Johnson (ref. 16). The 10-percent lives from the Weibull plots in figure 13

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

[Speed, 25 000 stress cycles per minute; maximum Hertz stress, 4823×10^6 N/m² (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 of 20	75
AISI 9310	4.18	9.43	2.31	10 of 10	--

^aNumber of fatigue failures out of number of specimens tested.

^bPercentage of time that 10-percent life obtained with AISI 9310 will have same relation to 10-percent life obtained with modified

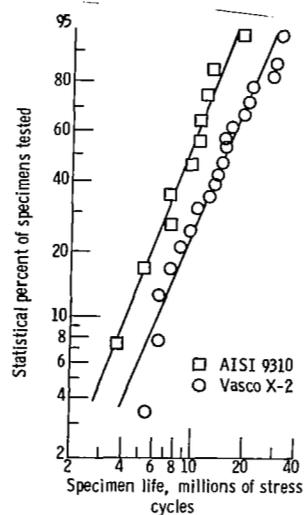


Figure 13. - Comparison of rolling-element fatigue lives of AISI 9310 and Vasco X-2 in rolling-contact tester. Speed, 25 000 stress cycles per minute; maximum Hertz stress, 4823×10^6 N/m² (700 000 psi); lubricant, MIL-L-7808; temperature, ambient.

(the life which 90 percent of the test bars will survive) were used for comparison purposes. The rolling-element fatigue life of the CVM modified Vasco X-2 was approximately 1.5 times that of the CVM AISI 9310.

The confidence number for these data given in table VI was 75. This confidence number indicates that 75 percent of the time the 10-percent fatigue life with modified Vasco X-2 will be greater than the 10-percent fatigue life with the AISI 9310 material.

Gear Endurance Tests

AISI 9310.—Tests were run with one group of CVM AISI 9310 gears at a maximum Hertz stress of $1.71 \times 10^9 \text{ N/m}^2$ (248 psi) with a synthetic paraffinic oil having an additive package (ref. 17). The results of these tests are shown in figure 14 and are summarized in table VII along with the test conditions.

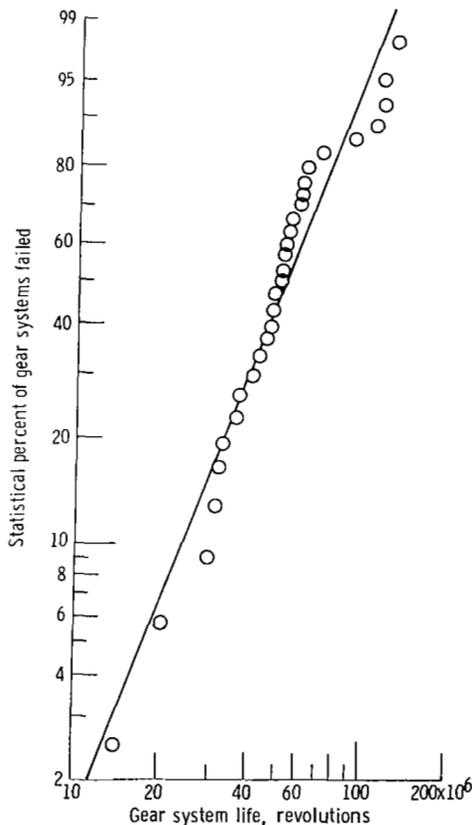


Figure 14. - Surface pitting fatigue life of CVM AISI 9310 spur gears. Pitch diameter, 8.39 centimeters (3.5 in.); speed, 10 000 rpm; lubricant, synthetic paraffinic oil; gear temperature, 350 K (170° F); maximum Hertz stress, $1.71 \times 10^9 \text{ N/m}^2$ (248 ksi).

TABLE VII. - SUMMARY OF GEAR FATIGUE LIFE RESULTS

[Pitch diameter, 8.89 centimeters (3.5 in.); spur gears; maximum Hertz stress, $1.71 \times 10^9 \text{ N/m}^2$ (248 ksi); speed, 10 000 rpm; lubricant, synthetic paraffinic oil; gear temperature, 350 K (170° F).]

Material	Heat treat procedure (see table III)	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 of 30	--
Modified Vasco X-2	Boeing Vertol	38.4×10^6	253×10^6	1.0	12 of 26	80
	NASA	0.8×10^6	27.6×10^6	0.53	18 of 21	99
	Curtis-Wright	3.3×10^6	8×10^6	2.1	19 of 19	99

^aNumber of fatigue failures out of number of gears tested.

^bPercentage 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.

The data were analyzed using the methods of Johnson (ref. 16). All surfaces of the AISI 9310 gears were carburized. Failure of the AISI 9310 gears was by surface pitting or spalling, which was of subsurface origin on or near the pitch-line of the gear tooth. No fracture of the gear teeth occurred. A typical spalled tooth is shown in figure 15.

Vasco X-2.—Tests were conducted with four groups of gears manufactured from three heats of Vasco X-2 and heat treated separately to different specifications and by different manufacturers. The material chemistry for the three heats of Vasco X-2 is given in table II. Heat treat specifications and source are given in table III. Of the four groups of gears, two were manufactured to the NASA specification. The only difference between the two NASA specified groups was that one group of gears was carburized on all sides while the other group was carburized on the flanks only.

Four pairs of gears having the NASA specification which were carburized on all sides were tested under the conditions first enumerated above. Four fracture failures occurred, one on each pair of gears tested. Failure was by tooth fracture at the tips of the teeth as shown in figure 16.



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Figure 15. - Representative fatigue spall of test gear material AISI 9310 steel.

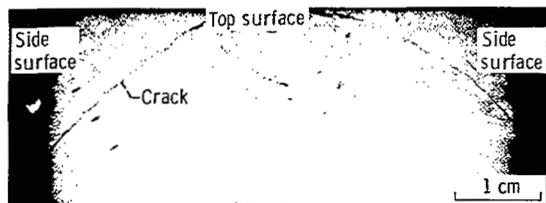


Figure 16. - Typical fracture of modified Vasco X-2 gear teeth with NASA specified heat treatment and carburized on all sides.

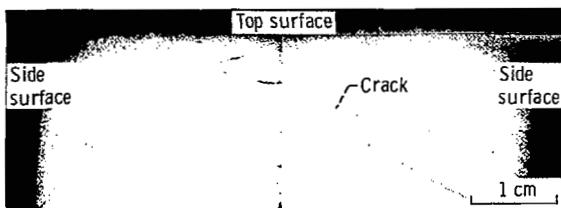
Two unfailed teeth on a single failed gear were cross-sectioned across the width of the tooth and across the profile. A cross section of the tooth width is shown in figure 17(a). The section revealed cracks around the corners of the tooth.

Unrun gears were also sectioned and similar cracks were found as shown in figure 17(b). Because the gears had not been run, it was evident that the cracks were caused by expansion of the carburized surface that produced excessive tensile stresses in the core material. The sides and ends of the gear teeth were not carburized on all subsequent gears.

The second group of Vasco X-2 gears heat treated to the NASA specification but carburized on the flanks only were tested. A total of 21 tests were conducted on nine pairs of gears. Results of these tests are shown on the Weibull plot of figure 18(a). Four gears failed by tooth fracture either at the root or

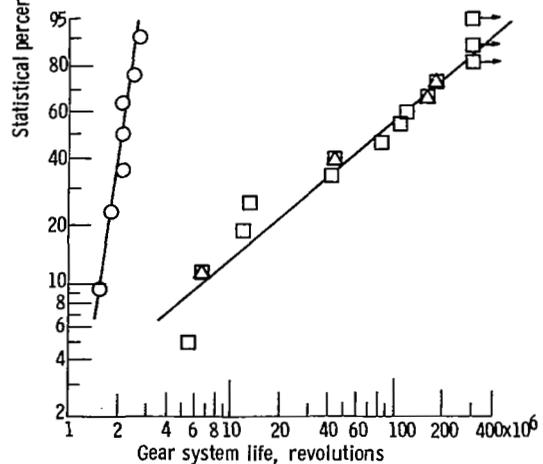
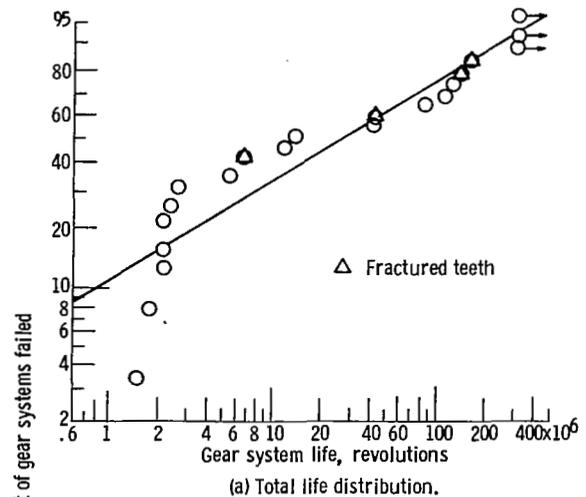


(a) Cross section of unfailed gear tooth from failed modified Vasco X-2 gear showing crack at each corner of tooth.



(b) Cross section of gear tooth from unrun modified Vasco X-2 gear showing crack formation.

Figure 17. - Cross section of unfailed and unrun modified Vasco X-2.



(b) Fatigue data of figure 18(a) divided into two groups indicating two distinct populations of gears with a distinct population distribution.

Figure 18. - Surface pitting fatigue life of CVM modified Vasco X-2 spur gears heat treated to NASA specifications. Pitch diameter, 8.39 centimeters (3.5 in.); speed, 10 000 rpm; lubricant, synthetic paraffinic oil; gear temperature, 350 K (170° F); maximum Hertz stress, $1.71 \times 10^9 \text{ N/m}^2$ (248 ksi).

pitch line of the gear tooth. These fractures occurred in conjunction with a surface fatigue pit. That is, a surface spall first occurred.

Examination of figure 18(a) strongly suggests that there appear to be two distinct populations of gear data each with a distinct population distribution. The data of figure 18(a) were divided and replotted in figure 18(b). The life dispersion of the two groups in figure 18(b) is typical of material that has variations in surface conditions caused during heat treating. The hardness of three randomly selected teeth in each gear were measured to determine their hardness variations if any. It was found that all the gears in the

low lived group in figure 18(b) had hardness values of Rockwell C 53 or less. The gears in the long lived group had Rockwell hardness values of Rockwell C 58 or above, with most gears in the Rockwell C 60 to 63 range. All the gears were heat treated in one batch.

Figure 19 is a photomicrograph of a cross section of two gears from these tests. Figure 19(a) shows a gear that failed in 3 hours (1.8×10^6 stress cycles), while figure 19(b) shows a gear that ran 285 hours (171×10^6 stress cycles).

The Rockwell C hardness of the case for the gear which ran 3 hours was Rockwell C 52 just below the surface and Rockwell C 49 on the surface. The case grain structure shows a loss of carbon at the surface and lower than normal carbon below the surface. This indicates that the case did not receive adequate carbon or lost carbon during heat treatment. The inadequate carbon may have been caused by chromium oxide on the surface which acts as a protective coating and prevents carburization. A large grain structure is also present in the case material. The 285-hour (171×10^6 -stress-cycle) gear has a case hardness of Rockwell C 57 and also shows evidence of inadequate carbon in the case but appears considerably better than the gear which ran 3 hours.

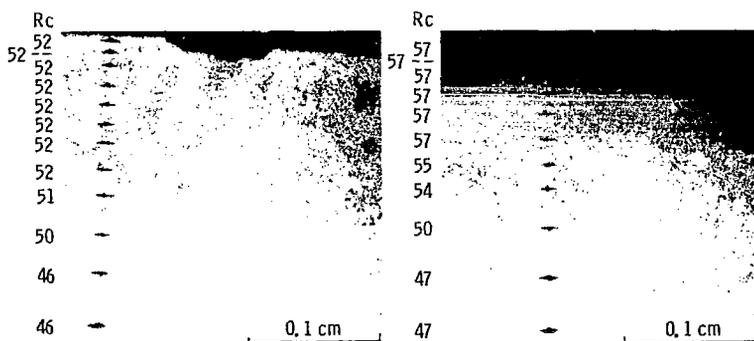
A third group of modified Vasco X-2 gears heat treated to the Curtis-Wright specification shown in table III was tested. The Curtis-Wright Corporation originally developed the modified Vasco X-2 together with the heat treatment for the steel (ref. 3). Nineteen (19) tests were conducted on five pairs of gears. The results of these tests are shown in figure 20(a) and are summarized in table VII. Figure 21(a) shows a typical fatigue spall for these gears. Figure 21(b) shows a cross section through a fatigue spall showing the case and case grain structure and the case and core hardness. The core hardness was Rockwell C 47. The case hardness was Rockwell C 57 which is somewhat

below the optimum of Rockwell C 61 for this material. The case grain structure reveals a somewhat lower than required carbon content which would account for the reduced hardness and low fatigue life.

The fourth group of modified Vasco X-2 gears was manufactured and surface fatigue tested. These gears were heat treated to the Boeing Vertol specification (table III) by one of their approved sources. The heat treatment was supervised by the Boeing Vertol quality control department to assure precise control of the complete carburization and heat treat process. Twenty-six (26) surface fatigue tests were conducted with eight pairs of the modified Vasco X-2 gears heat treated to the Boeing Vertol specification. The data are presented on Weibull coordinates and are shown in figure 20(b) and summarized in table VII. Fourteen of the 26 tests conducted were suspended at a cut off time of approximately 300×10^6 million stress cycles of operation with no damage.

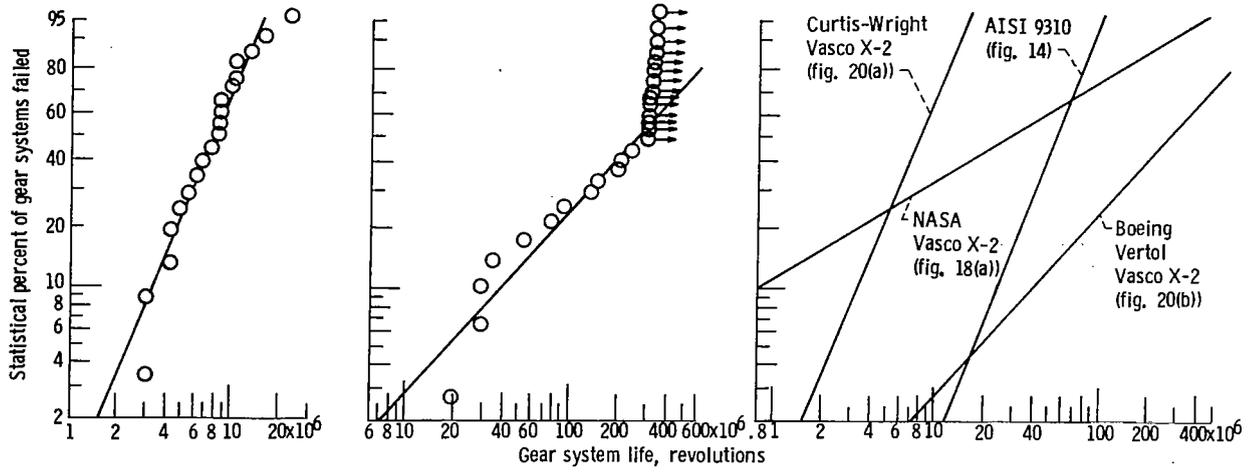
A typical fatigue spall is shown in figure 22(a). Figure 22(b) shows the grain structure of the case and core and the Rockwell C hardness. The hardness for the case was Rockwell C 60 and for the core Rockwell C 46.

Of the 12 in which failure occurred, five gears 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 tooth after 8 hours (4.8×10^6 stress cycles) in the overrun condition. The fractured portion of the gear is shown in figure 23. 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. However the AISI 9310 gears which were overrun on a fatigue spall did not have a single fracture failure.



(a) Running time, 1.8×10^6 stress cycles. (b) Running time, 171×10^6 stress cycles.

Figure 19. - Carburized case area of gears heat treated to NASA specification showing low carbon in case and lower than required case hardness for low and high cycle life gears. Maximum Hertz stress, 1.71×10^9 N/m² (248 ksi); speed, 10 000 rpm.

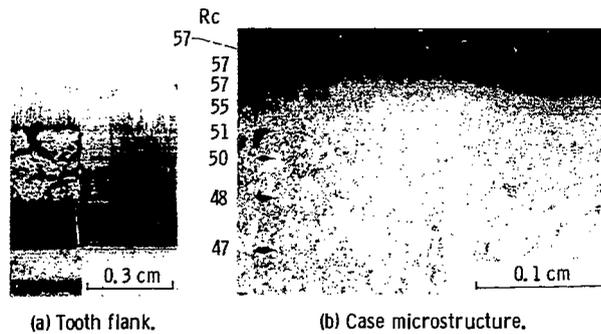


(a) Curtis-Wright heat treatment.

(b) Boeing Vertol heat treatment.

(c) Summary.

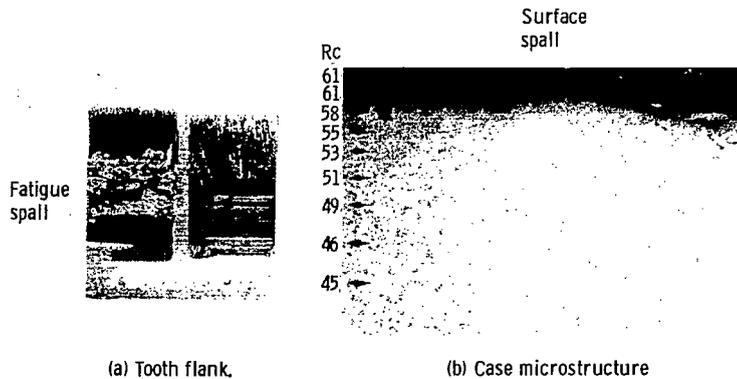
Figure 20. - Surface pitting fatigue life of CVM modified Vasco X-2 spur gears heat treated to different specifications. Pitch diameter, 8.39 centimeters (3.5 in.); speed, 10 000 rpm; lubricant, synthetic paraffinic oil; gear temperature, 350 K (170° F); maximum Hertz stress, $1.71 \times 10^9 \text{ N/m}^2$ (248 ksi).



(a) Tooth flank.

(b) Case microstructure.

Figure 21. - Typical fatigue spall for Curtis Wright heat treated modified Vasco X-2 gears. Maximum Hertz stress, $1.71 \times 10^9 \text{ N/m}^2$ (248 ksi); speed, 10 000 rpm.



(a) Tooth flank.

(b) Case microstructure

Figure 22. - Typical fatigue spall for Boeing Vertol heat treated modified Vasco X-2 gears. Maximum Hertz stress, $1.71 \times 10^9 \text{ N/m}^2$ (248 ksi); speed, 10 000 rpm.



Figure 23. - Gear tooth fracture through a fatigue spall of Boeing Vertol heat treated modified Vasco X-2. Maximum Hertz stress, 1.71×10^9 N/m² (248 ksi); speed, 10 000 rpm.

The surface fatigue life results for the three groups of gears made from the modified Vasco X-2 and the AISI 9310 gears are summarized in figure 20(c). A statistical comparison was made between the gear tooth pitting fatigue life of the three groups of modified Vasco X-2 gears and the CVM AISI 9310 and is summarized in table VII. The confidence number indicates the percentage of time the relative lives of the materials will occur in the same order. A confidence number of 95 percent which is equivalent to a 2 sigma confidence level is considered statistically significant. The difference between the pitting fatigue life of the AISI 9310 gears and the Boeing Vertol heat treat modified Vasco X-2 gears is statistically insignificant with a confidence number of 80 percent. The AISI 9310 and Boeing Vertol heat treated modified Vasco X-2 gears were statistically superior to both the NASA and Curtis-Wright heat treated modified Vasco X-2 gears.

Hardness effects.—It is well established that material hardness can have a significant effect on the pitting fatigue life of materials used for rolling-element bearings (ref. 18). In general, the higher the Rockwell C hardness of the rolling-element surface, the longer the fatigue life. The hardness of the case for the gears given the Curtis-Wright heat treatment was Rockwell C 57. For the gears heat treated to the NASA specification, the resultant hardnesses were Rockwell C 52 and 57 for the short lived and long lived groups, respectively, as shown in figure 18(b). The gears having the Boeing Vertol heat treatment, which produced the longest lives, had a Rockwell C hardness of 61. The AISI 9310 gears had a nominal case hardness of Rockwell C 60.

Using the relation from reference 18 for life and hardness

$$\frac{L_2}{L_1} = e^{0.1(R_{c2} - R_{c1})}$$

the 10-percent lives for the various groups of gears and the Rc specimens can be adjusted relative to AISI

TABLE VIII. - GEAR LIFE ADJUSTMENT BASED ON HARDNESS

Material	Heat treat procedure (see table III)	Nominal Rockwell C hardness	Data source	Relative 10-percent life	
				L_E experimental	L_A adjusted based on hardness ^a
AISI 9310	-----	60	Fig. 14	1	1
Modified Vasco X-2	Boeing Vertol	61	Fig. 20 (b)	1.67	1.51
	NASA	57	Fig. 18 (b)	0.27	0.36
		52	Fig. 18 (b)	0.05	0.16
	Curtis-Wright	57	Fig. 20 (a)	0.14	0.19

$$^a L_A = L_E e^{0.1(R_{cE} - R_{cA})}$$

where

- L_A adjusted relative life
- L_E experimental relative life
- R_{cA} adjusted hardness taken as Re60
- R_{cE} nominal Rockwell C hardness

9310 for equal hardness. This equation was developed for AISI 52100 bearing material, but is the best available equation for the other materials. These results are shown in table VIII. The adjusted life difference in surface pitting life between the modified Vasco X-2 using the Boeing Vertol heat treatment and the AISI 9310 is not considered statistically significant. The other Vasco X-2 gear materials show significantly reduced lives.

Using the hardness life equation for the two groups of gears in figure 18(b), a calculated life ratio of 1.7 is obtained. The actual experimental life ratio shown in figure 18(b) is 3.9.

Concluding Remarks

From the data presented it is apparent that the modified Vasco X-2 can be a reasonably good gear material only if very stringent quality control is exercised during heat treatment. This is apparently necessary because of the 5 percent chromium in the material which forms a protective chromium oxide coating and prevents carburization. Unless the prescribed heat treatment method is closely followed and controlled, poor carburization will result. As evidenced by the data presented herein, poor gear life will result.

A primary objective of the research reported herein was to determine the comparative pitting fatigue life of the modified Vasco X-2 as it is applied to spur gears with gears made from AISI 9310. However, even with good surface fatigue life and carefully controlled carburization, there is a good probability the material is somewhat low in fracture toughness (refs. 19 and 20). Low fracture toughness may result in material fracture under adverse stress conditions.

Summary of Results

Endurance tests were conducted with four groups of spur gears manufactured from three heats of consumable electrode vacuum melted (CVM) modified Vasco X-2. Each heat was subjected to a different heat treatment procedure. Additional endurance tests were conducted with spur gears which were manufactured from a single heat of AISI 9310 steel. Test conditions for the gears included a gear temperature of 350 K (170° F), a maximum Hertz stress of 1.71×10^9 N/m² (248 ksi) and a speed of 10 000 rpm. The gears were lubricated with a synthetic paraffinic oil with a 5-percent extreme-pressure additive. Bench-type rolling-element fatigue tests were also conducted to compare the rolling-element fatigue life of modified Vasco X-2 material with AISI 9310. Test conditions were a speed of 12 500 rpm, a maximum Hertz stress of 4.83×10^9 N/m² (700 ksi) and a MIL-L-7808 type lubricant. Hardness measurements were made to elevated temperatures on samples of AISI 9310 and modified Vasco X-2 materials. The following results were obtained:

1. The difference in the 10-percent life of the long lived gears manufactured from modified Vasco X-2, and those manufactured from AISI 9310 was not statistically significant. These results were similar to those obtained with the rolling-element fatigue tests.

2. Variations in lives among the different heats of the modified Vasco X-2 and heat treatment procedures can be primarily attributed to heat treatment quality control and resultant case hardness. The higher the case hardness the longer the life.

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

4. A surface fatigue spall on the tooth surface of a modified Vasco X-2 gear can act as a nucleus of a tooth fracture failure.

5. At temperatures to approximately 422 K (300° F) there was no significant difference in the decrease in hot hardness with temperature between the modified Vasco X-2 and the AISI 9310 materials.

Lewis Research Center,

National Aeronautics and Space Administration,
Cleveland, Ohio, March 25, 1980,
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		15. Supplementary Notes	
16. Abstract <p>Endurance tests were conducted with four groups of spur gears manufactured from three heats of consumable electrode vacuum melted (CVM) modified Vasco X-2. Endurance tests were also conducted with gears manufactured from CVM AISI 9310. Bench-type rolling-element fatigue tests were conducted with both materials. Hardness measurements were made to 811 K (1000⁰ F). There was no statistically significant life difference between the two materials. Life differences between the different heats of modified Vasco X-2 can be attributed to heat treat variation and resultant hardness. Carburization of gear flanks only can eliminate tooth fracture as a primary failure mode for modified Vasco X-2. However, a tooth surface fatigue spall can act as a nucleus of a tooth fracture failure for the modified Vasco X-2.</p>			
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