



Surface Fatigue Life of CBN and Vitreous Ground Carburized and Hardened AISI 9310 Spur Gears

Dennis P. Townsend
NASA Lewis Research Center, Cleveland, OH
P.R. Patel
Bell Helicopter Textron, Forth Worth, TX

Abstract:

Spur gear surface endurance tests were conducted to investigate CBN ground AISI 9310 spur gears for use in aircraft applications, to determine their endurance characteristics and to compare the results with the endurance of standard vitreous ground AISI 9310 spur gears. Tests were conducted with VIM-VAR AISI 9310 carburized and hardened gears that were finish ground with either CBN or vitreous grinding methods. Test conditions were an inlet oil temperature of 320 K (116°F), an outlet oil temperature of 350 K (170°F), a maximum Hertz stress of 1.71 GPa (248 ksi), and a speed of 10,000 rpm.

The CBN ground gears exhibited a surface fatigue life that was slightly better than the vitreous ground gears. The subsurface residual stress of the CBN ground gears was approximately the same as that for the standard vitreous ground gears for the CBN grinding method used.

Introduction

Grinding of carburized and hardened gear teeth for aircraft application has been standard practice for many years. Grinding is required to produce the required accuracy and surface finish necessary for improved life, reduced noise, and dynamic loads for aircraft gears. Until a few years ago, the method

used for grinding hardened gears was the standard vitreous grinding wheel. The vitreous grinding method typically produces a very shallow compressive stress [<0.013 mm (0.0005 in.)] on the surface of the ground part, but has very little effect on the subsurface compressive residual stress.

A few years ago cubic boron nitride (CBN) grinding wheels were introduced for grinding gears and other parts.⁽¹⁾ The CBN grinding wheel allows a much greater rate of stock removal of hardened parts without producing the grinding burns that are prevalent with vitreous grinding. The CBN crystals have a high thermal conductivity compared to the vitreous material and con-

duct the heat away from instead of into the part. In addition, the CBN crystals are very sharp and very hard and produce a chip-like cutting action. When a hardened gear or other part is ground very hard with considerable force, a subsurface residual compressive stress is developed below the surface.⁽²⁾ This subsurface residual compressive stress has been shown to improve the subsurface fatigue life of gears and bearings.^(3,4) The CBN grinding of carburized and hardened AISI 9310 steel spur gears should, therefore, produce equivalent or improved surface fatigue life.

The objectives of the research reported herein were (1) to investigate CBN grinding as a method for finishing aircraft-type gears; (2) to determine the surface endurance characteristics of CBN ground carburized and hardened AISI 9310 steel spur gears; (3) to compare the results with standard vitreous ground carburized and hardened AISI 9310 steel spur gears. To accomplish these objectives, tests were conducted with two groups of gears manufactured from one lot of material. One group of spur gears from that lot were CBN ground. For comparison purposes, the other group of spur gears were manufactured by vitreous grinding. The gears had a gear pitch diameter of 8.89 cm (3.50 in.) and 3.2 module (8 diametral pitch). Test conditions included an oil inlet temperature of 320 K

(116°F) that resulted in an oil outlet temperature of 350 K (170°F), a maximum Hertz stress of 1.71 GPa (248 ksi), and a shaft speed of 10,000 rpm.

Apparatus and Procedures

GEAR TEST APPARATUS — The gear fatigue tests were performed in the NASA Lewis Research Center's gear fatigue test apparatus (Fig. 1a). 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

AUTHORS:

MR. D.P. TOWNSEND is a gear consultant for NASA and numerous industrial companies. Townsend earned a BSME from the University of West Virginia. During his career at NASA he has authored over eighty papers in the gear and bearing research area. For the past several years, he has served in active committee roles for ASME. Presently he is a member of the ASME Design Engineering Executive Committee.

MR. P.R. PATEL is a principal engineer at Bell Helicopter Textron, Ft. Worth, TX. He has worked in the areas of materials and process control for aircraft drives systems. He holds an M.S. in Metallurgical Engineering from the University of Minnesota and an M.B.A. from the University of Dallas. Mr. Patel is a member of the American Society for Metals and the American Helicopter Society.

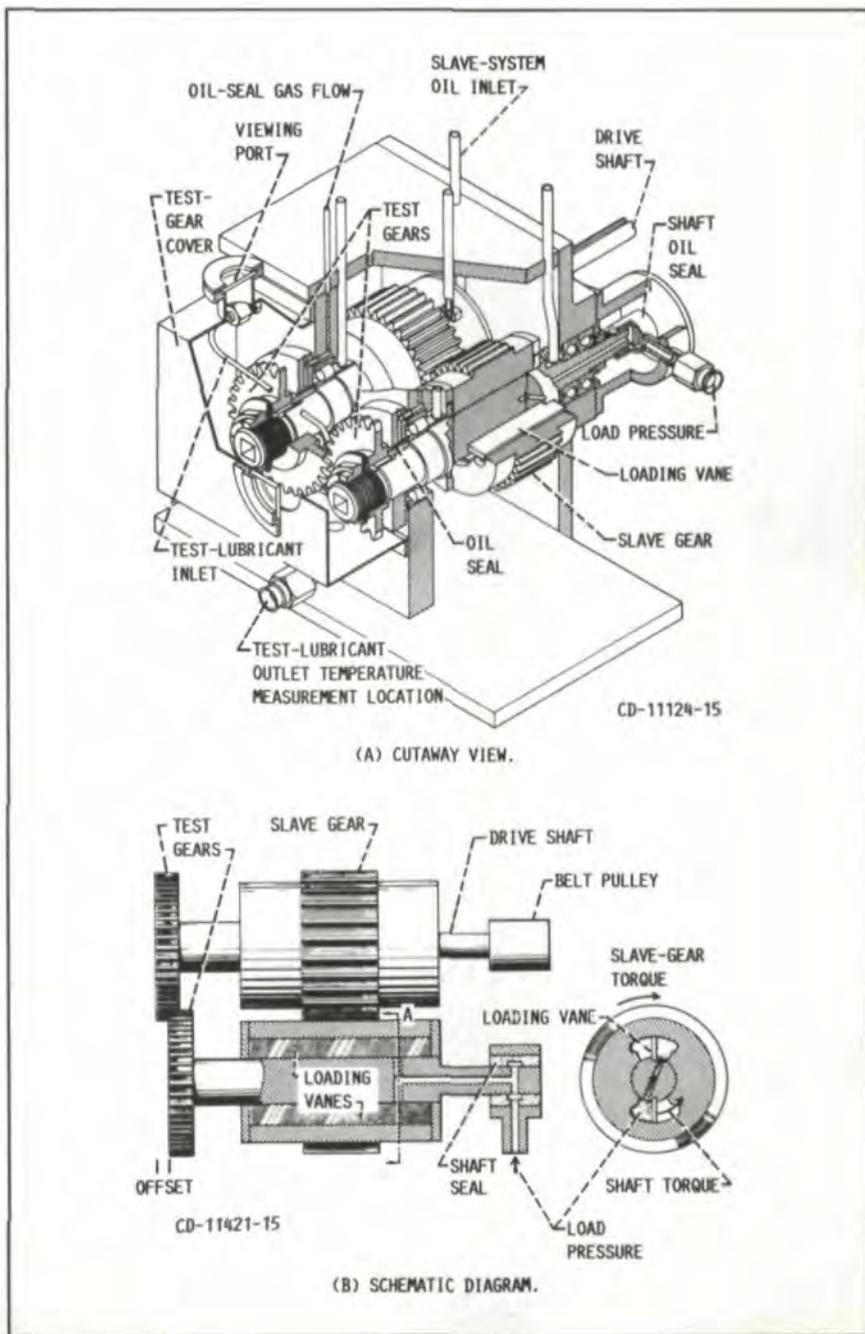


Fig. 1 — NASA Lewis Research Center's Gear Fatigue Test Apparatus.

Table I. — 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 diameter, cm (in.)	7.988 (3.145)
Root fillet, cm (in.)	0.10 to 0.15 (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.)	0.025 (0.010)
Tip relief, cm (in.)	0.0013 (0.0005)
Tooth width, cm (in.)	0.64 (0.25)

Table II. — Grinding Data
For Vitreous and CBN Ground Spur Gears

	Wheel speed, rpm	Grit size	Finish μm ($\mu\text{in.}$)	Table speed, sec/pass	Number of passes per tooth	Depth of cut per pass	Time to grind one gear
Vitreous	1600	60	0.36 (14)	2	36	0.018 mm (0.0007 in.)	15 hr
CBN	3400	70	0.30 (12)	6	5	0.13 mm (0.005 in.)	20 min

Table V. — Heat Treat Procedure for Test Gears

Pre-carburize heat treatment	
Normalize	1725°F for 1 hr Air cool
Harden	1500°F for 1 hr Oil quench
Temper	1000°F for 4 hr
Carburize	1700°F for 6.5 hr 1.0 percent carbon potential
Post-carburize heat treatment	
Sub-critical anneal	1150°F for 2 hr Air cool
Harden	1500°F for 1 hr Oil quench
Sub-zero treat	-115°F for 4 hr
Temper	300°F for 4 hr Air cool

Table III. — Data for Gear Used for Residual Stress Measurements

Number of teeth	31
Diametral pitch	8.5
Pressure angle, deg	22
Pitch diameter, cm (in.)	9.264 (3.647)
Face width, cm (in.)	3.386 (1.333)

Table IV. — Chemical Composition of Test Materials by Percent Weight

Element	AISI 9310 gears
Carbon (core)	0.10
Manganese	.60
Phosphorus	.006
Sulfur	.005
Silicon	.24
Copper	.04
Chromium	1.35
Molybdenum	.16
Vanadium	.01
Nickel	3.37
Iron	Balance

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 μm nominal fiber-glass 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.

TEST GEARS — A photograph of the test gears is shown in Fig. 2. The dimensions of the gears is given in Table I. All gears had a nominal surface finish on the tooth face of $0.2 \mu\text{m}$ ($8 \mu\text{in.}$) rms or better. Typical surface finish charts for both grinding methods are shown in Fig. 3. All gears have a standard 20° involute profile with tip relief. The tip relief was 0.0013 cm (0.0005 in.) starting at the highest point of single tooth contact. One group of gears was ground with a vitreous grinding wheel with speed, feed, and metal removal rate as shown in Table II. The second group of gears were ground with a CBN form grinder with speed, feed, and metal removal rate as shown in Table II.

Residual stress profiles were established using a gear configuration described in Table III, to determine the difference between the two grinding techniques. For baseline condition, one gear was tested in as-carburized condition. The stress measurements were made using x-ray diffraction technique at the approximate pitch diameter of the gears. The results of residual stress measurements are summarized in Fig. 4.

TEST MATERIAL — The gears were manufactured from vacuum induction melted, vacuum arc remelted (VIM VAR) AISI 9310 steel. The nominal chemical composition of the gears is given in Table IV. The heat treatment procedure for the test gears is given in Table V. The case and core properties of the test gears are given in Table VI. Photomicrographs of the case and core of a test gear are given in Figs. 5a and b.

TEST LUBRICANT — All the gears were lubricated with a single batch of synthetic paraffinic oil, which was the standard test lubricant for the gear tests.



Fig. 2 — Test Gear Configuration.

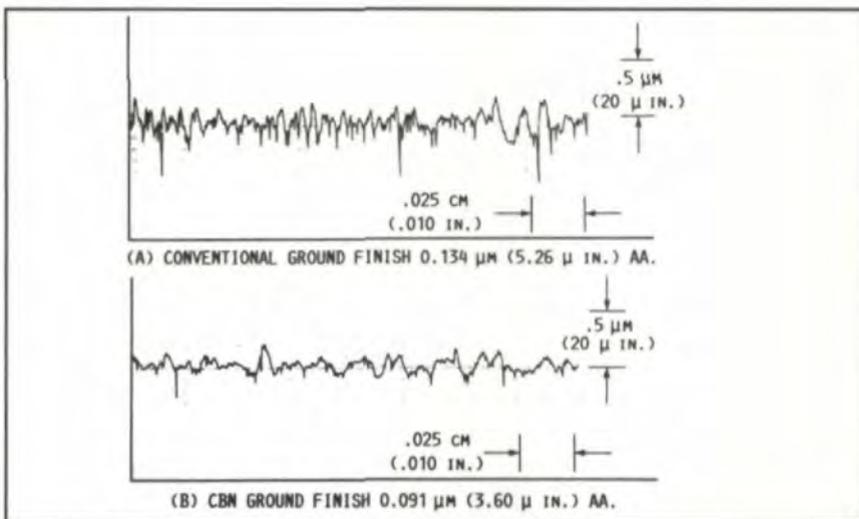


Fig. 3 — Surface Finish Measurement in Profile Direction With .010 Cutoff.

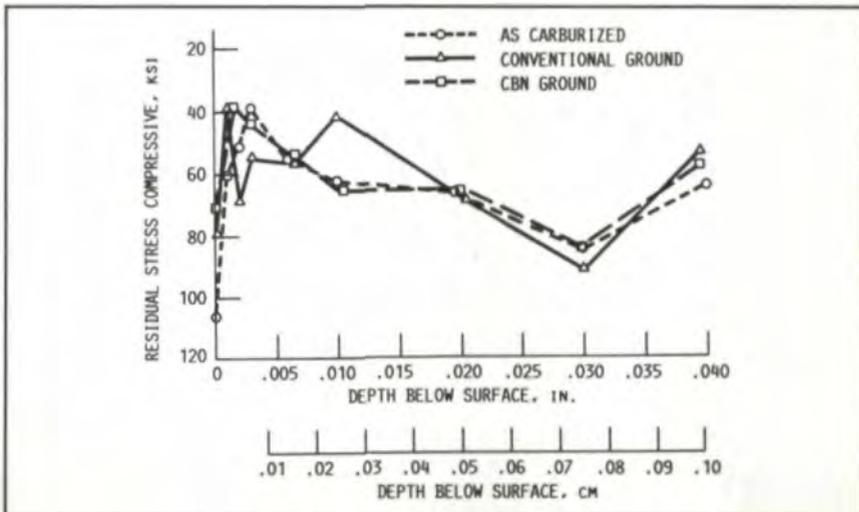


Fig. 4 — Residual Stress Measurements on Tooth Flank of AISI 9310 Spur Gears Ground by Vitreous and CBN Grinding Wheels.

Table VI. — Case and Core Properties of Test Gears

	Conv. Ground	CBN Ground
Surface hardness, HRC	61.5	63.0
HRC 60 depth, mm (in.)	0.45 (0.018)	0.53 (0.021)
HRC 50 depth, mm (in.)	0.99 (0.039)	0.97 (0.038)
Core hardness, HRC	38.0	38.0
Retained austenite, percent	6.0	6.6



(A) Case



(B) Core

Fig. 5—Photomicrographs of the Case and Core Material for Test Gears.

The physical properties of this lubricant are summarized in Table VII. Five percent of an extreme pressure additive, designated *Lubrizol 5002* (partial chemical analysis given in Table VII) was added to the lubricant.

TEST PROCEDURE— 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 cm (0.120 in.) tooth-surface overlap to give a surface load width on the gear face of 0.28 cm (0.110 in.); thereby allowing for an edge radius on 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 per unit width of 1230 N/cm (700 lb/in.) for 1 hr. The load was then increased to 5800 N/cm (3300 lb/in.), which resulted in a 1.71 GPa (248 ksi) pitch line maximum Hertz stress. At the pitch line load the tooth bending stress was 0.21 GPa (30 ksi) if plain bending was assumed. However, because there was an offset load, there was an additional stress imposed on the tooth bending stress. Combining the bending and torsional moments gave a maximum stress of 0.26 GPa (37 ksi). This bending stress did not include the effects of tip relief, which would also increase the bending stress.

Since the offset test method may introduce edge loading effects, the method was originally checked with and without crowned gears. There was no difference between crowned and uncrowned gears. Also all fatigue spalls with uncrowned gears originate evenly along the tooth flank and never start at the edge location. This is proof that the offset test condition is an acceptable method for surface fatigue testing.

Operating the test gears at 10,000 rpm gave a pitch line velocity of 46.55 m/sec (9163 ft/min). Lubricant was supplied to the inlet mesh at 800 cm³/min (49 in.³/min) and 320±6 K (116±10°F). The lubricant outlet temperature was nearly constant at 350±3 K (170±5°F). The tests ran continuously (24 hr/day) until the rig was automatically shut

down by the vibration detection transducer (located on the gearbox adjacent to the test gears) or until 500 hours of operation without failure were completed. The lubricant circulated through a 5 μm fiberglass filter to remove wear particles. For each test, 3.8 liters (1 gal.) of lubricant were used. At the end of each test, the lubricant and filter element were discarded. 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 Reference 5. It was assumed for this film thickness calculation that the gear surface 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 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 μm (13 $\mu\text{in.}$), which gave an initial ratio of film thickness to composite surface roughness (h/σ) of 1.15 at the 1.71 GPa (248 ksi) pitch line maximum Hertz stress.

Each pair of gears was considered as a system and, hence, a single test. Test results were evaluated using Weibull plots calculated by the method of Johnson.⁽⁶⁾ (A Weibull plot is the number of stress cycles versus the statistical percent of gear system failed.)

Results and Discussion

One lot of VIM VAR AISI 9310 steel spur gears was divided into two groups and endurance tested. One group was ground by a vitreous grinding wheel, while the second group was ground by a CBN form grinding wheel. Test conditions consisted of a tangential tooth load of 5800 N/cm (3300 lb/in.), which produced a maximum Hertz stress of 1.7 GPa (248 ksi), and a speed of 10,000

Table VII. — Lubricant Properties

Property	Synthetic Paraffinic oil plus additives*
Kinematic viscosity, cm^2/sec (c) at:	
244 K (-20°F)	2500×10^{-2} (2500)
311 K (100°F)	31.6×10^{-2} (31.6)
372 K (210°F)	5.5×10^{-2} (5.5)
477 K (400°F)	2.0×10^{-2} (2.0)
Flash point, K ($^\circ\text{F}$)	508 (455)
Fire point, K ($^\circ\text{F}$)	533 (500)
Pour point K ($^\circ\text{F}$)	219 (-65)
Specific gravity	0.8285
Vapor pressure at 311 K (100°F), mm Hg (or torr)	0.1
Specific heat at 311 K (100°F), J/(kg) (K); Btu/(lb)($^\circ\text{F}$)	2190 (0.523)

* Additive Lubrizol 5002 (5 vol %); phosphorus 0.03 vol %; sulfur, 0.93 vol %.

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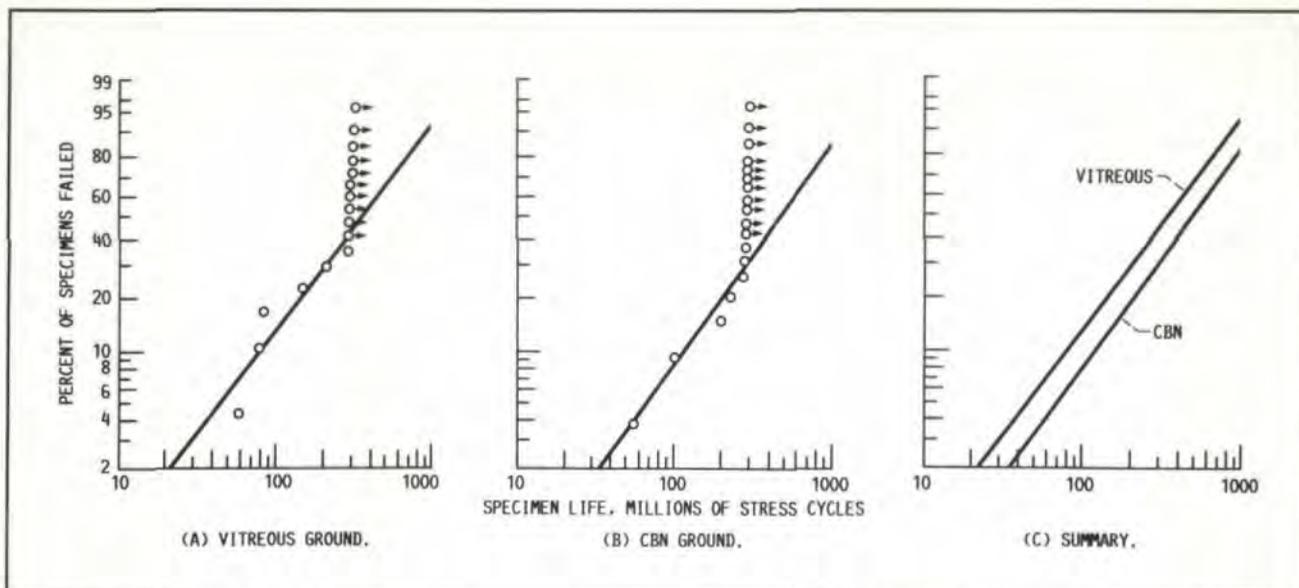


Fig. 6—Surface Fatigue Life of Carburized, Hardened, Ground and Shot Peened Test Gears. Speed 10,000 rpm; Maximum Hertz Stress, 1.71 GPa (248 ksi); Temperature, 350 K (170° F); Lubricant, Synthetic Paraffinic With 5% E P Additive.



Fig. 7—Typical Fatigue Spall for AISI 9310 Gears.

rpm. The gears failed by classical subsurface pitting fatigue. The pitting fatigue life results of these tests are shown in the Weibull plots of Fig. 6 and are summarized in Table VIII.

Pitting fatigue life results for the gears that were ground by the vitreous grinding wheel are shown in Fig. 6a. The 10 and 50% lives were 82.5×10^6 and 371×10^6 stress cycles (137 and 618 hr), respectively. The Weibull slope was 1.25. The failure index (i.e., the number of fatigue failures out of the number of sets tested) was 6 out of 16. A typical fatigue spall that occurs near the pitch

line is shown in Fig. 7. This is a typical fatigue spall similar to those observed in rolling element fatigue tests. The pitch line pitting is the result of a high subsurface shearing stress which develops subsurface cracks. These subsurface cracks propagate into a crack network 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 gear systems that were ground by a CBN form grinder are shown in Fig. 6b. The 10 and 50% surface fatigue lives were 122.7×10^6 and 502×10^6 stress cycles (205 and 837 hr), respectively. The Weibull slope was 1.34. The failure index was 7 out of 18. The 10% surface fatigue life of the CBN ground gears was $\sim 1\frac{1}{2}$ times that of the standard vitreous ground gears. The confidence number was 60%, which indicates that there are 600 chances out of 1000 tests that the 10% life of the CBN ground gears will be superior to the 10% life of the vitreous ground gears. This indicates that there is not a lot of statistical significance to the life difference between the two groups of gears. However, it does indicate that the CBN gears are at least equivalent in life to the vitreous ground gears or slightly better. The equivalent residual stress profile of the two methods of grinding would also indicate that the fatigue life should be approximately the same. A more vigorous CBN grinding could induce some additional compressive residual stress;

Table VIII. — Spur Gear Fatigue Life Results

[Pitch diameter, 8.89 cm (3.50 in.); maximum Hertz stress, 1.71 GPa (248 ksi); speed, 10,000 rpm; lubricant, synthetic paraffinic oil; gear temperature, 350 K (170° F).]

Material	Gear system life, revolutions		Weibull slope	Failure index*	Confidence number at 10% level**
	10% life	50% life			
Standard ground VIM-VAR AISI 9310	82.5×10^6	371×10^6	1.25	6 out of 16	—
CBN ground VIM-VAR AISI 9310	122.7×10^6	502×10^6	1.34	7 out of 18	60

*Number of surface fatigue failures out of number of gears tested.

**Percentage of time that 10% life obtained with AISI 9310 gears will have the same relation to the 10% life obtained with Ex-53 gears or CBS 1000 M.

thereby, improving the surface fatigue life.⁽²⁻³⁾ A summary of the fatigue lives of the two groups of ground gears are given in Fig. 6c.

Summary of Results

Spur gear endurance tests were conducted to investigate CBN ground AISI 9310 spur gears for use in aircraft gear applications, to determine their endurance characteristics and to compare the results with the endurance of standard vitreous ground AISI 9310 spur gears. Tests were conducted with VIM-VAR AISI 9310 carburized and hardened gears that were finished ground with either CBN or vitreous grinding methods. Test conditions were an inlet oil temperature of 320 K (116°F), an outlet oil temperature of 350 K (170°F), a maximum Hertz stress of 1.71 GPa (248 ksi), and a speed of 10,000 rpm. The following results were obtained:

1. The CBN ground gears exhibited a surface fatigue life that was slightly better than the vitreous ground gears.
2. The subsurface residual stress of the CBN ground gears was approximately the same as that for the standard vitreous ground gears for the CBN grinding method used.

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