IN-22065

NASA Technical Memorandum 87330

Surface Fatigue and Failure Characteristics of Hot Forged Powder Metal AISI 4620, AISI 4640, and Machined AISI 4340 Steel Spur Gears

(NASA-TM-87330) SURFACE FATIGUE AND FAILURE CHARACTERISTICS OF HOT FORGED POWDER METAL AISI 4620, AISI 4640, AND MACHINED AISI 4340 STEEL SPUR GEARS (NASA) 34 p CSCL 13I

N86-31889

Unclas
G3/37 43093

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Prepared for the
1986 Annual Meeting of the American Society of Lubrication Engineers
Toronto, Canada, May 12-15, 1986

NASA

SURFACE FATIGUE AND FAILURE CHARACTERISTICS OF HOT FORGED POWDER METAL AISI 4620, AISI 4640, AND MACHINED AISI 4340 STEEL SPUR GEARS

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E-3024

Abstract

Spur gear surface fatigue endurance tests were conducted to investigate hot forged powder metal AISI 4620 and 4640 steel for use as a gear material, to determine endurance characteristics and to compare the results with machined AISI 4340 and 9310 steel gear materials.

The as-forged and unground AISI 4620 gear exhibited a 10 percent fatigue life that was approximately one-fourth of that for AISI 9310 and less than one-half that for the AISI 4340 gears. The forged and finish ground AISI 4620 gears exhibited a 10 percent life approximately 70 percent that of AISI 9310 and slightly better than that of AISI 4340. The AISI 4640 hot forged gears had less fracture toughness and slightly less fatigue life than the AISI 4620 test gears.

INTRODUCTION

There has always been a need to reduce the manufacturing cost associated with the manufacture of gears. A large part of this cost is involved in cutting the gear teeth to rough dimensions and then finish grinding of the teeth after the hardening heat treat operation. A method such as gear forging that could reduce or eliminate these machining and grinding steps would offer considerable cost savings for production type gears. High pressure compacting and sintering of powder metal gear has been used for many years, however the strength of this type material does not allow its use for anything other than light duty gears. In recent years the powder metal hot forging process has come into service whereby the powder metal is pressed into a preform, sintered at a suitable temperature around 1480 K (2200 °F) and then forged into shape while at the sintering temperature (1,2). This process greatly improves the density and strength of the powder metal preform to nearly the strength of solid wrought metal. Some automotive gears are currently being manufactured by this process with considerable savings over machined gears (1). Also the powder manufacturing process now makes it possible to taylor an alloy to a specific need by combining the right amounts of certain metal powders.

The hot forging powder metal process has the potential of providing low cost, high strength and high temperature gears for tanks, trucks, aircraft, and other applications. Some recent programs conducted by the government and industry (3-4) have shown promise for the manufacture of hot forged powder metal components for various applications. In addition, gears forged from AISI M-50 material with integral forged teeth have shown improvement in bending fatigue strength as a result of the grain flow pattern developed in the tooth root from the forging process (5).

The objective of the research reported herein was to compare under closely controlled test conditions, the fatigue lives and failure modes of standard test spur gears manufactured from machined AISI 9310 and 4340 and hot forged powder metal AISI 4620 and 4640. In addition, compare one group of finish ground hot forged powder metal AISI 4620 with a group of net shape hot forged powder metal AISI 4620 spur gears.

GEAR TEST APPARATUS

The fatigue tests were performed in the NASA Lewis' gear 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 gear-box. 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 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.

TEST GEARS

A typical forged and unfinished test gear is shown in Fig. 2. All the forged test gears had oversized bores and had to be fitted with inserts to match the NASA test gearbox shaft dimensions. Four different groups of test gears were evaluated. Three groups of test gears were hot forged P/M, carburized and hardened after forging. Two of these groups were hot forged P/M AISI 4620; one group of which was finish-ground while the other group was tested in the as-forged dimension. The third hot forged P/M group was AISI 4640, carburized and hardened and tested in the as-forged dimension. A fourth group of test gears were standard machined AISI 4340 steel, carburized, hardened, and ground. The four abovementioned groups were compared with previously tested AISI 9310 gears that were carburized, hardened, and ground. Dimensions for the test gears are shown in Table 1. The finish ground gears were AGMA class 12 with a surface finish of 0.41 μm (16 μin.) rms. The as-forged gears were not dimensionally inspected. The nominal chemical composition of the test gears is given in Table 2.

Gear Forging

The NASA test gears were P/M (powder metal) hot forged from both AISI 4620 and 4640 steel powder preforms. The test gears were forged on 6.2 mN (700 ton) crank press with a 0.25 (10 in.) stroke. The preform was developed from an analytical program for the test gear and is shown in Fig. 3. The die set used for the hot forged P/M gears is shown in Fig. 4. A number of iterations were required before the optimum forging sequence for the AISI 4620 and 4640 powder metal preform was established. The actual forging sequence is shown in Table 3. The green preform had to be sintered and preheated before forging. Therefore, a preheat oven was located next to the forging press so that the preheated preforms could be manually transferred from the oven to the forging press in a short time.

The as-pressed preforms were sprayed with a forging lubricant, placed in the oven and sintered (preheated) at 1477 K (2200 °F) for at least 30 min. The 30 min were required to prevent cracks forming on the end of the teeth during forging. The dies and tools were preheated to 561 K (550 °F) and the dies were lubricated with a forging lubricant before forging the gear. After the preform was sintered it was again sprayed with a forging lubricant and manually transferred in about 4 sec to the forging dies where it was forged to shape with integral teeth in one blow. One series of 4620 and 4640 steel test gears were forged with teeth oversized by 0.2 to 0.25 mm (0.008 to 0.010 in.) so they could be finish ground to an AGMA class 12 tolerance.

After the oversized gears were forged, a set of punches and a ring die were machined for hot forging a set of P/M AISI 4620 and 4640 gears directly to finished dimensions. In order to accomplish the finish dimensions, the die temperature had to be held at 453 to 469 K (335 to 385 °F). If the die temperature was above these temperatures and the transfer time slower than 4 sec, the gears would be oversized. If the die temperature was less than these temperatures, the gear would be undersized. The dimensions of the test gear die cavity for forging to finished dimensions is shown in Table 4.

Gear samples were cross sectioned and etched to study the porosity and grain flow patterns. Figure 5 shows the typical flow pattern for the hot P/M forged gears.

Most of the forged gears had cracks around the circumference of the center hub. These cracks were caused by the way the metal flowed during forging and has no effect on the gear performance. There was some porosity in the gear tooth tips which is extremely difficult to eliminate. A few gears had cracks in the gear teeth as shown in Fig. 6 that would be detrimental to gear performance. There was also some foreign material included that is detrimental to gear performance as shown in Figs. 5 and 6. These inclusions are from the powder supplied for the gear forging.

The hot forged P/M AISI 4620 and 4640 test gears were carburized and hardening according to the heat treatment schedule given in Table 5. The hot forged P/M AISI 4640 and the standard machined AISI 4340 were originally through hardened but did not have sufficient case hardness for the stressing involved in the test and therefore were subsequently carburized and rehardened.

The micro-hardness showing the case and core hardness for the three materials are shown in Figs. 7(a), (b), and (c).

TEST LUBRICANT

All the gears were lubricated with a single batch of synthetic paraffinic oil. The physical properties of this lubricant are summarized in Table 6. Five percent of an extreme pressure additive, designated Lubrizol 5002 (partial chemical analysis given in Table 6), was added to the lubricant.

Test Procedure

After the test gears were cleaned to remove their protective coating, they were installed in 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 an actual load surface on the gear face of 0.28 cm (0.110-in.), 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 hr. The load was then increased to 5784 N/cm (3305 lb/in.) for all gears (except the AISI 4640 test gears) which results in a 1.71×10^9 N/m^2 (248 000-psi) pitch-line maximum Hertz stress. The AISI 4640 test gears were run at a load of 4625 N/cm (2645 lb/in.) because of tooth fracture at the higher load. This gave a Hertz stress of 1.53×10^9 N/m^2 (222 000 psi). At the pitch-line load of 5784 N/cm (3305 lb/in) 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. The combined bending stress for the AISI 4640 gears was 0.208×10^9 N/m^2 (29 600 psi).

The test gears were run at 10 000 rpm which results in a pitch-line velocity of 46.55 m/sec (9163 ft/min). Lubricant was supplied to the inlet mesh at 800 cm^3/min at 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 either automatically shut down by the vibration detection transducer, located on the gearbox adjacent to the test gears or completed 500 hr without failure. The lubricant circulated through a 5-μm fiberglass filter to remove wear particles. For each test, 3800 cm^3 (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 Ref. (6). 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 oil temperature at the inlet 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 μm (13 μin.), which gave an initial ratio of film thickness to composite surface roughness (h/σ) of 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 (7).

RESULTS AND DISCUSSION

Two groups of hot forged powder metal spur gears and two groups of standard machined and ground spur gears were tested under a load of 5784 N/cm (3305 lb/in.) which produced a maximum Hertz stress of 1.7 MPa (248 000 psi).

A third group of hot forged powder metal gears was tested at a Hertz stress of 1.53×10^9 N/m^2 (222 000 psi). Two of the three groups of hot forged powder metal gears were tested in the as-forged condition while the third group was finish ground to AGMS class 12 prior to testing. The test lubricant was a synthetic paraffinic oil with an extreme pressure additive package. The gears failed by either surface pitting fatigue or tooth bending fracture.

Test Results

The test results for all the gears are shown in Fig. 8 and Table 7. Test results were statistically evaluated using the method of Ref. (7). For this evaluation a pair of gears was considered as one test. These results plotted on Weibull coordinates represent those gear systems that failed by surface pitting fatigue and by tooth fracture after surface pitting. Weibull coordinates are the log of the reciprocal of the probability of survival graduated as the statistical percent of specimens failed (ordinate) against the log time to failure or system life (abscissa). The results for the AISI 9310 steel gears are shown in Fig. 8(a). The 10 percent pitting fatigue life of the AISI 9310 steel spur gears is approximately 20 million cycles. There were 18 surface fatigue failures out of 18 total tests.

The results of the tests with hot forged and finish ground powder metal AISI 4620 steel spur gears are shown in Fig. 8(b). Ten of the 18 gears tested failed by surface fatigue without a fracture while the remaining 8 gears failed first by surface fatigue followed by a tooth fracture shortly after the fatigue spall occurred. With 8 of 18 surface fatigue failures resulting in tooth fractures, it would appear that the hot forged powder metal AISI 4620 does not exhibit a high degree of fracture toughness that is desired for gears. This may be the result of impurities in the powder used to make the preforms or to some cracks or porosity resulting from the hot forging operation. Both of these defects were present to some degree in the hot forged gears. The 10 percent surface fatigue life of the hot forged and finish ground powder metal AISI 4620 test gears was 13 million cycles which is approximately 65 percent that of the AISI 9310 gears.

The statistical results of the tests with the as-hot-forged powder metal AISI 4620 gears are shown in Fig. 8(c). The as-forged gears were carburized and hardened after forging to net size and were not ground or finished after the forging and heat treatment. Since there is always some distortion during heat treatment, these gears did not have the same gear tooth accuracy as the finish ground AISI 4620 gears. Seven of the 13 gears tested failed by tooth fracture in the root area without a prior fatigue spall. The six remaining gears failed by classical surface fatigue pitting. There was more scatter in the failures for the as-forged AISI 4620 gears as evidenced by the reduced slope of the Weibull plot compared to the finish ground forged AISI 4620 gears. This would be expected with less accurate gears, since there can be much higher loads on some teeth.

The 10 percent life for the as-forged AISI 4620 gears was 5 million stress cycles which is approximately 38 percent of that for the finish ground AISI 4620 forged gears and 25 percent of that for the AISI 9310 gears.

From the results it is evident that these gears also exhibited a low fracture toughness.

The statistical test results for the hot forged powder metal AISI 4640 gears are shown in Fig. 8(d). These gears were tested in the as-forged and heat treated condition without any subsequent finishing operation. The first attempts to run at the standard test condition of 1.71×10^9 N/m^2 (248 ksi) Hertz stress, however, resulted in several gears experiencing tooth fracture on start up or after a very short running time. Therefore, these gears were run at a lower Hertz stress of 1.53×10^9 N/m^2 (222 ksi). The results of testing at this lower Hertz stress were plotted in Fig. 8(d) and the 10 and 50 percent life determined for that condition. Valves for life at the higher Hertz stress were then calculated using the life ratio equation from Ref. (8) for gears. Reference (8) gives the life ratio as a function of the inverse load ratio to the 4.5 power as follows:

$$\frac{L_1}{L_2} = \left(\frac{P_2}{P_1}\right)^{4.5}$$

Since the maximum Hertz stress for gears is a function of the square root of the load, the life equation for the ratio of the maximum Hertz stress would then be

$$\frac{L_1}{L_2} = \left(\frac{S_2}{S_1}\right)^{9}$$

The life of the hot forged AISI 4640 gears can then be compared with other gear test data at the same Hertz stress condition. Thus the 10 percent life for the hot forged unfinished AISI 4640 test gears was calculated to be 11.6×10^6 stress cycles at the 1.71×10^9 N/m^2 (248 ksi) Hertz stress.

There were 2 tooth fractures of the hot forged AISI 4640 at the lower Hertz stress. One was a tooth fracture at the root without a fatigue spall after 24 million stress cycles and the other was a fracture through a fatigue spall after 134 million stress cycles. Since the hot forged powder metal AISI 4640 was manufactured from the same basic powder as the AISI 4620 with the addition of carbon it would be expected that the fracture toughness would not be any better than the AISI 4620 and might even be worse with the addition of more carbon to the base powder. This was confirmed by the test results producing more tooth fractures at the higher load.

The statistical results for the AISI 4340 standard machined, carburized and hardened steel spur gears is shown in Fig. 8(e). These gears were originally through hardened and ground but were too soft to run at the (248 ksi) Hertz stress. Therefore, they were, carburized and hardened, with- out further finishing to increase the case hardness. The final case hardness was Rockwell RC 62-64. However, since there is some distortion of the material during carburization and hardening the gear tooth accuracy was reduced considerably. There was, therefore, considerable scatter in the fatigue data as shown by the reduced slope of the Weibull plot. There were three gears that had tooth fractures through a fatigue spall. There were also 6 gear pairs that ran to the 500 hr cutoff without failure and were treated as suspensions resulting in 12 failures out of 18 total tests. The 10 percent life of the AISI 4340 machined gears was 11.6 million stress cycles. This is approximately 58 percent of the life of the AISI 9310 gears. It would be expected that the AISI 4340 would have a better 10 percent life if the gears were manufactured with closer tolerance. The statistical results of all the tests are summarized in Fig. 8(f) and shows that the 10 percent life of all the other test gears were less than the AISI 9310 while the 50 percent life of the AISI 4340 was better than the AISI 9310.

Failure Analysis

A typical fatigue spall and cross section through the spall of the hot forged P/M and finish ground AISI 4620 is shown in Figs. 9(a) and (b). Metallurgical examination indicated that the fatigue spalls were of subsurface origin and initiated at or near the pitch diameter in the region of maximum Hertz stress. The grain flow pattern can be seen in the gear tooth cross section as the flow of metal was outward during the forging process. The large amount of impurities and graphite flakes can also be seen in the cross section. Figure 10 is a higher magnification of the case and core structure where the smaller dark spots are the impurities from the original powder. These impurities will act as stress risers and result in reduced fatigue life for the gears. Eight of the gears failed by tooth fracture out of the 18 total tests for this test series. This is an indication of the poor fracture toughness of this material and is partially the result of considerable amount of impurities in the forged grains. Typical gear tooth fracture for the several materials tested are shown in Fig. 11.

A typical fatigue spall and cross section through the spall of the as-forged AISI 4620 gears is shown in Fig. 12. These gears had the same composition as the forged and finish ground AISI 4620 but they were forged to net size then heat treated and tested without additional finishing. The crack in the gear tooth cross section appears to be from a forging lap but did not cause a tooth fracture in this instance. These gears had shorter fatigue lives than the finish ground gears and had a slightly higher percentage of tooth fractures, 7 out of 14 total tests.

A typical fatigue spall and cross section of a failed hot forged PM AISI 4640 test gear is shown in Fig. 13. Here also the impurities of the material can be seen. The AISI 4640 was made with the same base metal powder as the AISI 4620 with the addition of graphite flakes to increase the carbon content. Photomicrographs of the case and core section of the AISI 4640 are shown in Fig. 14. The effect of the increased carbon can be seen when comparing the AISI 4640 photomicrographs with those of the AISI 4620 (Fig. 10). The hot forged PM AISI 4640 was forged to net shape, carburized and hardened without additional finishing. At the standard maximum Hertz stress of 1.71×10^9 N/m^2 (248 ksi), there were several quick tooth fractures. At the lower stress condition of 1.53×10^9 N/m^2 (222 ksi) there were only 2 of 13 tests that failed by tooth fracture. Typical tooth fractures for this material are shown in Fig. 11(b) and (c). Figure 11(b) shows a fracture through a spall, while

Fig. 11(c) shows a root fracture. Apparently the additional carbon in this material reduced the fracture toughness to the point where the gears could not be operated at the higher stress level without tooth fracture. The calculated 10 percent life at 1.71×10^9 N/m^2 (248 ksi) for the AISI 4640 was less than the finish ground forged AISI 4620 but greater than the unfinished forged AISI 4620. Therefore the surface fatigue life of the forged AISI 4640 was not improved over the AISI 4620 and the fracture toughness was reduced somewhat.

A typical fatigue spall and cross section of a failed machined AISI 4340 test gear is shown in Fig. 15. These gears were originally machined, through hardened and ground. However they were not hard enough to give a reasonable surface fatigue life at the 1.71×10^9 N/m^2 (248 000 ksi) maximum Hertz stress, so they were carburized and hardened without additional finishing. This carburizing and hardening produced some distortion which would affect the scatter and the fatigue life. The result of the fatigue tests shown in Fig. 8(e) indicate considerable data scatter and a 10 percent fatigue life that was nearly half that of the AISI 9310 material. There were also three tooth fractures out of 12 tests which would indicate a fairly low fracture toughness for the AISI 4340 material. A typical tooth fracture for the AISI 4340 is shown in Fig. 11(d).

SUMMARY OF RESULTS

Three groups of 8.89 cm (3.5 in.) pitch diameters hot forged powder metal spur gears and two groups of machined spur gears were endurance tested at 350 K (170 °F) and 10 000 rpm. Four of the gear groups were tested at a maximum Hertz stress of 1.71×10^9 N/m^2 (248 000 psi) and one group was tested at 1.53×10^9 N/m^2 (222 000 psi) maximum Hertz stress. The hot forged powder metal gears were AISI 4620 and 4640 and the machined gears were AISI 4340 and 9310. The lubricant was synthetic paraffinic with 5 percent EP additive. The endurance results of the test gears were compared with each other and with the standard AISI 9310 gears. All tests were run under identical conditions except for the lower Hertz stress on one group.

The following results were obtained:

1. The pitting fatigue life of the finish ground hot forged powder metal AISI 4620 gears was approximately 70 percent that of the standard AISI 9310 gears run under identical conditions.

2. The pitting fatigue life of the as-forged carburized and hardened powder metal AISI 4620 gears was approximately one-fourth that for the AISI 9310 gear and approximately one-third that of the same material that was finish ground before testing.

3. The addition of more carbon to the hot forging powder to make AISI 4640 gears did not improve the surface fatigue life over the AISI 4620 and reduced the fracture toughness of the hot forged powder metal gears.

4. The AISI 4340 machined, through-hardened and ground spur gears that were subsequently carburized and rehardened without refinishing exhibited considerable scatter in pitting fatigue life and had a 10 percent life approximately one-half that of the AISI 9310 and nearly equal to the hot forged and finished ground powder metal AISI 4620 gears.

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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)
Tip relief, cm (in.)	0.0013 (0.0005)

TABLE 2. - CHEMICAL COMPOSITION OF TEST MATERIALS BY PERCENT WEIGHT

Element	AISI 9310	AISI 4340	AISI 4620[a]	AISI 4640[a]
Carbon (core)	0.11	0.38/0.43	0.17/0.22	0.38/0.43
Manganese	.58	0.6/0.8	0.2/0.3	0.2/0.3
Molybdenum	.13	0.2/0.3	0.3/0.5	0.3/0.5
Chromium	1.38	0.70/0.90	---------	---------
Copper	.21	---------	---------	---------
Silicon	.26	0.20/0.35	<0.05	<0.05
Nickel	3.2	1.65/2.00	1.65/2.00	1.65/2.00
Phosphorous	.003	<0.04	<0.04	<0.04
Sulfur	.004	<0.04	<0.04	<0.04
Iron	Balance	Balance	Balance	Balance

[a]Made from water-atomized AISI 4600 powder and graphite powder to obtain desired carbon level.

TABLE 3. - POWDER FORGING SEQUENCE PROCESS VARIABLES

Step	Variables present	Selected variable values
Powder type Selection	Production method	Water atomized
	Initial alloy distribution	Prealloyed
	Particle size distribution	100 mesh (forging quality)
Compaction	Lubricant	Zinc stearate
	Lubrication method	Die wall
	Compaction tooling	Tool steel dies (hard tooling)
	Compaction pressure	Sufficient to densify powder to 80 percent of theoretical density
Sintering	Atmosphere	Dissociated ammonia
	Temperature	(2200 °F) 1480 K
	Time	30 min at temperature
Forging	Press type	Mechanical
	Preform temperature	1480 K (2200 °F)
	Tooling temperature	453 to 469 K (355 to 385 °F)
	Transfer time	4 to 8 sec
	Forging pressure	Sufficient for die fill
	Time in tooling	
	Lubricant	Deltaforge 31 or 33
	Post-forging cooling	Quench in oil

TABLE 4. - DIMENSIONS OF NASA TEST GEAR DIE CAVITY FOR FORGING OF GEARS WITH NET TEETH[a]

Number of teeth	28
Diametral pitch	8
Circular pitch cm (in.)	1.000 (0.396)
Chordal tooth thickness cm (in.)	0.490 (0.193)
Pressure angle cm (in.)	20°
Pitch diameter cm (in.)	8.974 (3 533)
Major diameter cm (in.)	9.616.(3.786)
Minor diameter cm (in.)	8.062 (3.174)
Root fillet radius cm (in.)	0.152 (0.060)
Tip radius cm (in.)	0.025 (0.010)

[a]Punches have a 0.005 cm/0.010 cm (0.002 /0.004 in.) clearance gap per side.

TABLE 5. - HEAT TREATMENT PROCEDURE FOR GEAR MATERIALS TESTED

Step	Process	AISI 9310	AISI 4620 AISI 4640 AISI 4340
1	Carburize	1172 K (1650 °F) 8 hr	1172 K (1650 °F) for 0.08 cm (0.033 in.) eff case depth
2	Temperature	922 K (1200 °F) 10 hr	922 K (1200 °F) 2.5 hr
3	Austentize or harden	1088 K (1500 °F) 2.5 hr	1116 K (1550 °F) 2.5 hr
4	Oil quench	Oil quench	Oil quench
5	Deep freeze	190 K (-120 °F)	190 K (-20 °F) 3.5 hr
6	Temperature	450 K (350 °F) 2 hr	422 K (300 °F) 2 and 2 hr

TABLE 6. - LUBRICANT PROPERTIES

Property	Synthetic paraffinic oil plus additives[a]
Kinematic viscosity, cm^2/sec (cs) at:	
244 K (-20 °F)	2500×10^{-2} (2500)
311 K (100 °F)	31.6×10^{-2} (31.6)
372 K (210 °F)	5.7×10^{-2} (5.7)
477 K (400 °F)	2.0×10^{-2} (2.0)
Flash point, K (°F)	508 (455)
Fire point, K (°F)	533 (500)
Pour point, K (°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)(°F))	676 (0.523)

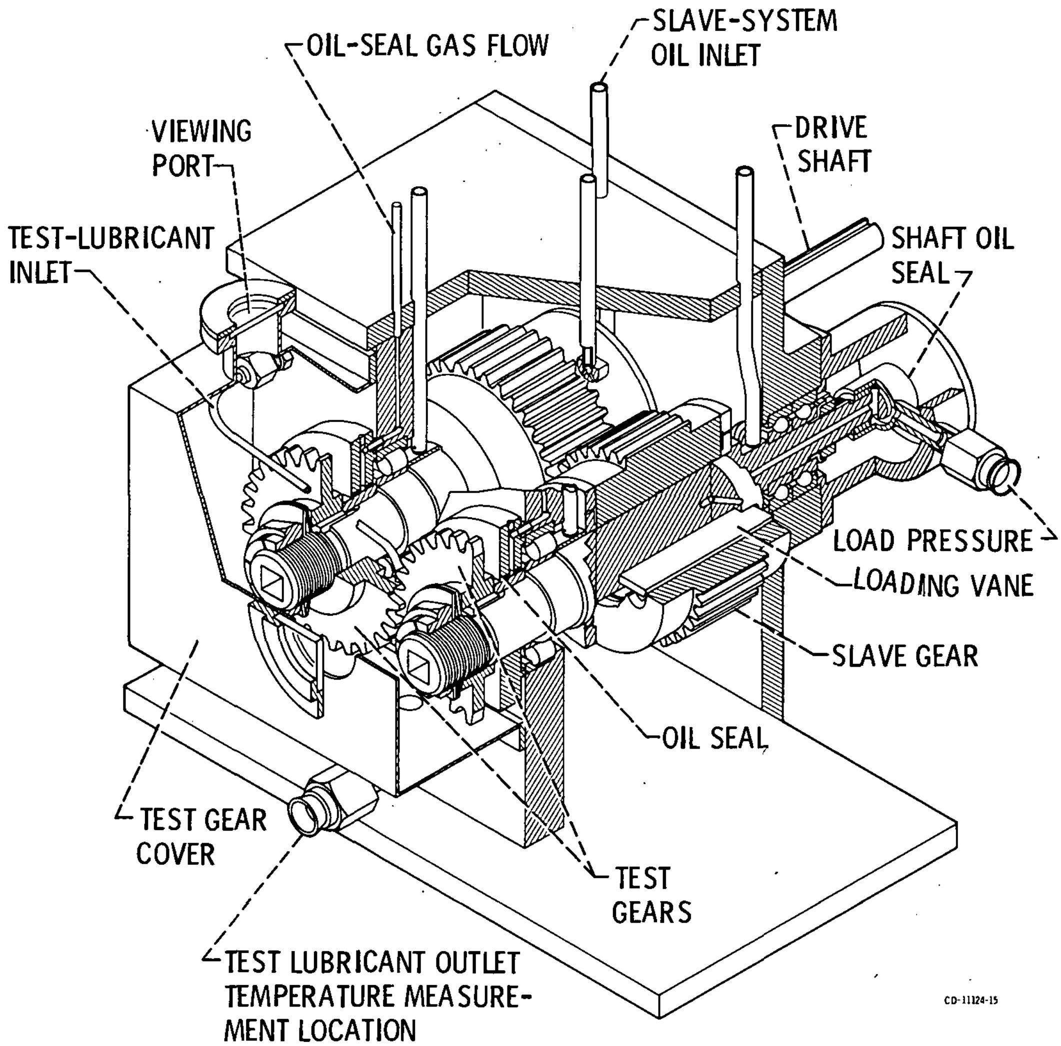
[a]Additive, Lubrizol 5002 (5 vol %); phosphorus, 0.03 vol %, sulfur, 0.93 vol %.

TABLE 7. - SPUR GEAR FATIGUE LIFE RESULTS

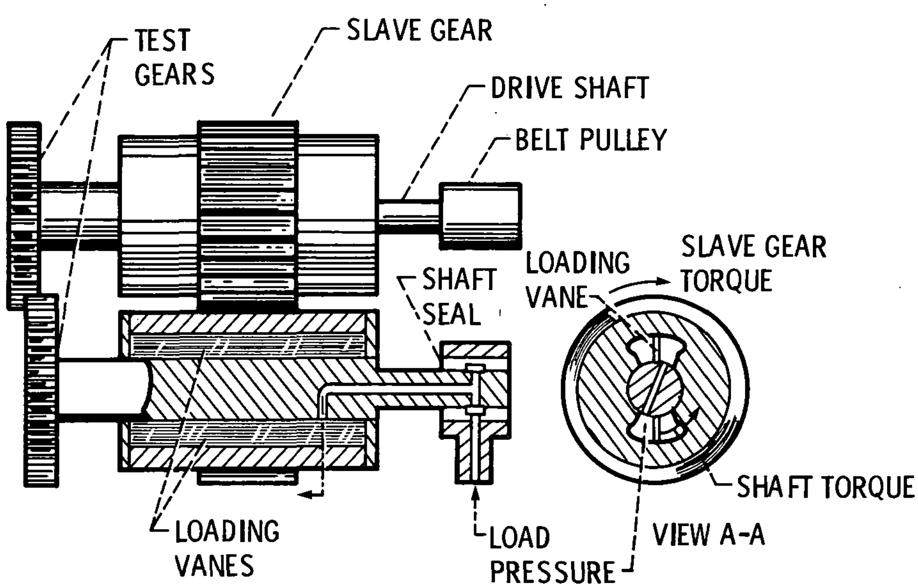
[Pitch diameter, 8.89 cm (3.50 in.); maximum Hertz stress, 1.71 GPa (248 ksi); speed, 10 000 rpm; lubricant, synthetic paraffinic oil; gear temperature, 350 K (170 °F).]

Material	Gear system life, revolutions		Weibull slope	Failure index[a]	Confidence number at 10-percent level[a]
	10-percent life	50-percent life			
AISI 9310	19×10^6	46×10^6	2.1	18 out of 18	----------
AISI 4620 Finish ground	13×10^6	34.4×10^6	1.94	18 out of 18	74 percent
AISI 4620 As-forged	4.85×10^6	24.2×10^6	1.17	13 out of 13	96 percent
AISI 4640 Calculated[b]	10.6×10^6	35.9×10^6	1.54	13 out of 13	80 percent
AISI 4340	11.6×10^6	165.2×10^6	.71	12 out of 18	70 percent

[a]Number of failures out of number of tests.
[b]Tests run at 1.53 GPa (222), results interperted to 1.71 GPa (248 ksi) for comparison.



(a) Cutaway view.



(b) Schematic diagram.

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

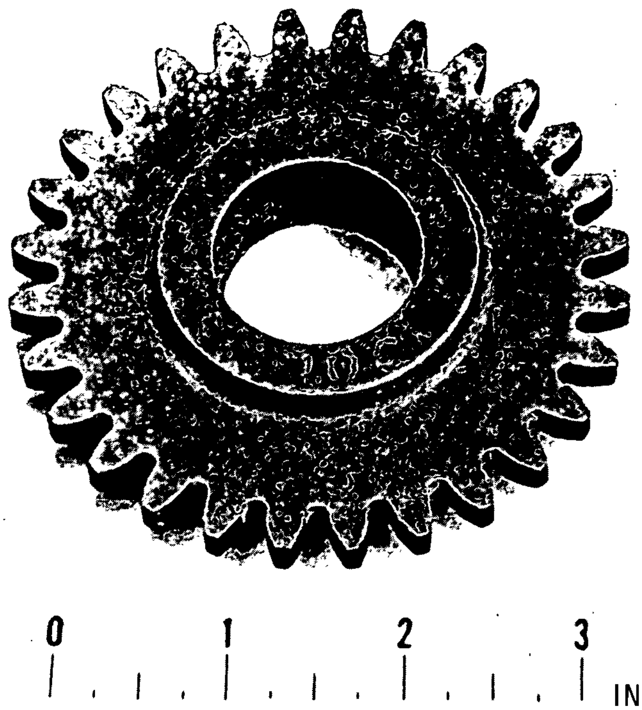


Figure 2. - Forged test gear by P/M Forging.

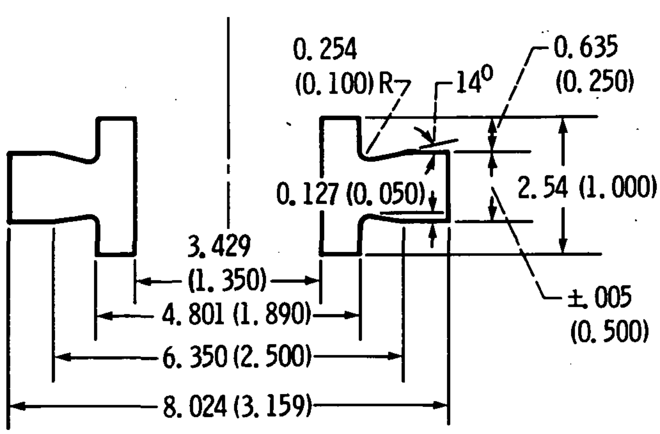
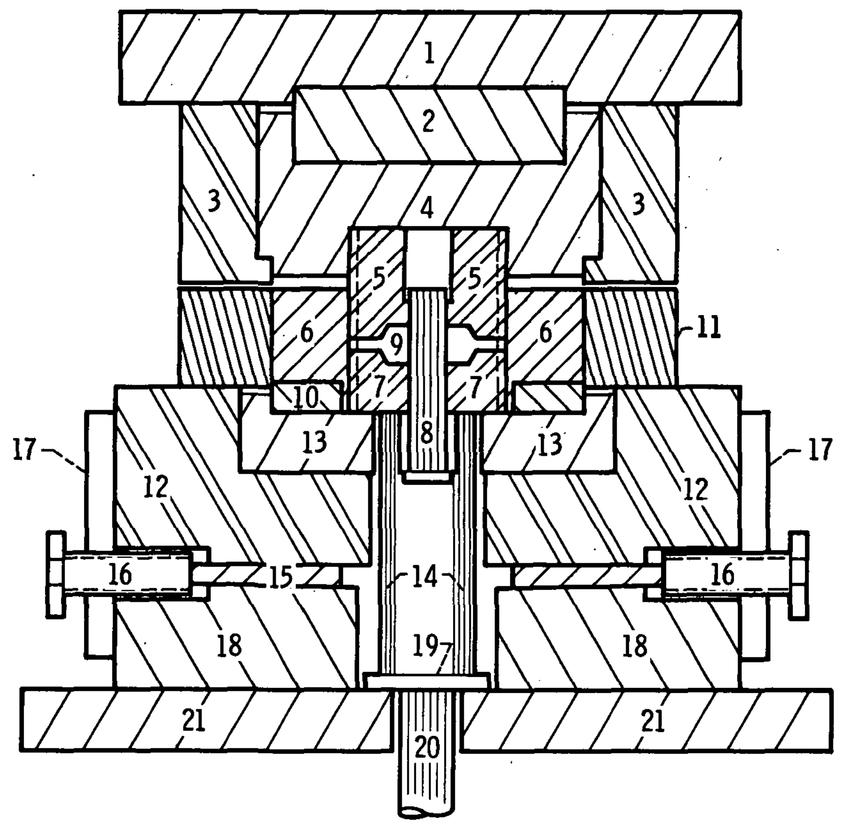


Figure 3. - Test gear preform. Dimensions are in centimeters (inches) with precision of ±0.025 (±0.010) unless specified.



1 TOP BOLSTER
2 LOAD CELL
3 SUPPORT RING
4 BACKER BLOCK
5 TOP PUNCH
6 RING DIE
7 BOTTOM PUNCH
8 CORE ROD
9 FORGED GEAR
10 DIE SUPPORT RING
11 SUPPORT-CLAMP RING
12 SUB-BACKER BLOCK
13 BACKER BLOCK
14 EJECTOR PINS
15 WEDGE
16 WEDGE ADJUSTER SCREWS
17 ALIGNMENT PLATE
18 TAPERED BASE PLATE
19 EJECTOR PIN SEAT
20 EJECTOR ROD
21 BOTTOM BOLSTER

Figure 4. - Die set for P/M gear forging. Modular or expendable members are pieces 5-8.

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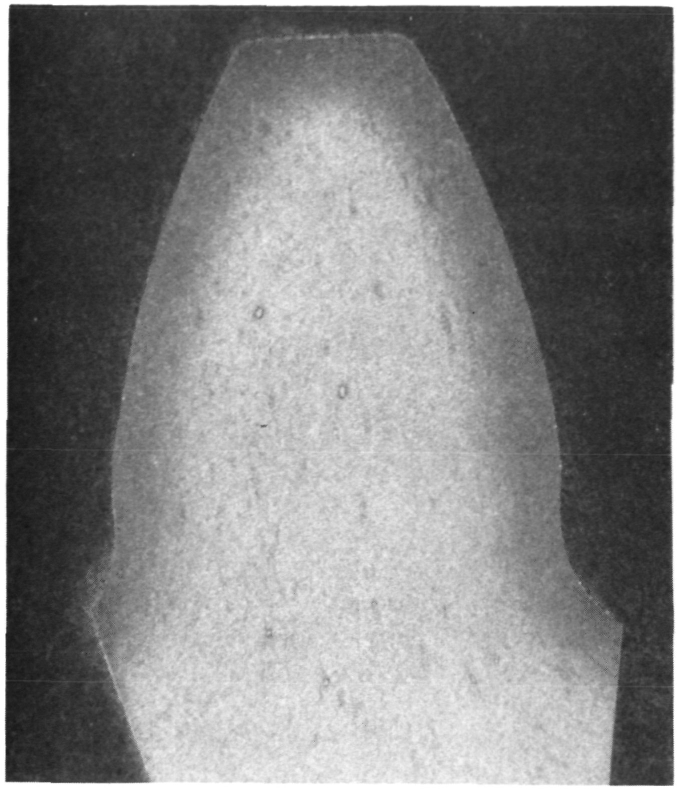


Figure 5. - Grain flow pattern of hot forged powder metal AISI 4640 gear tooth.

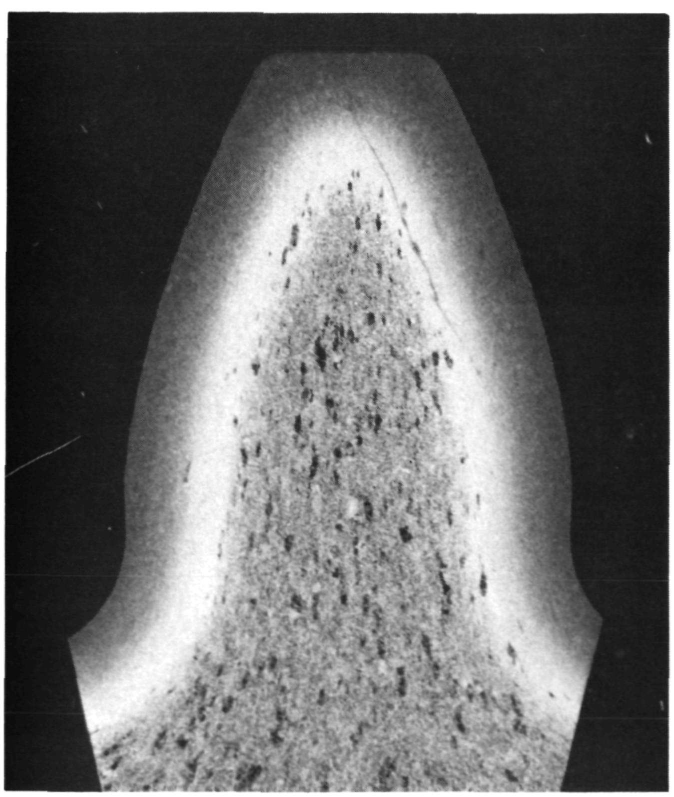
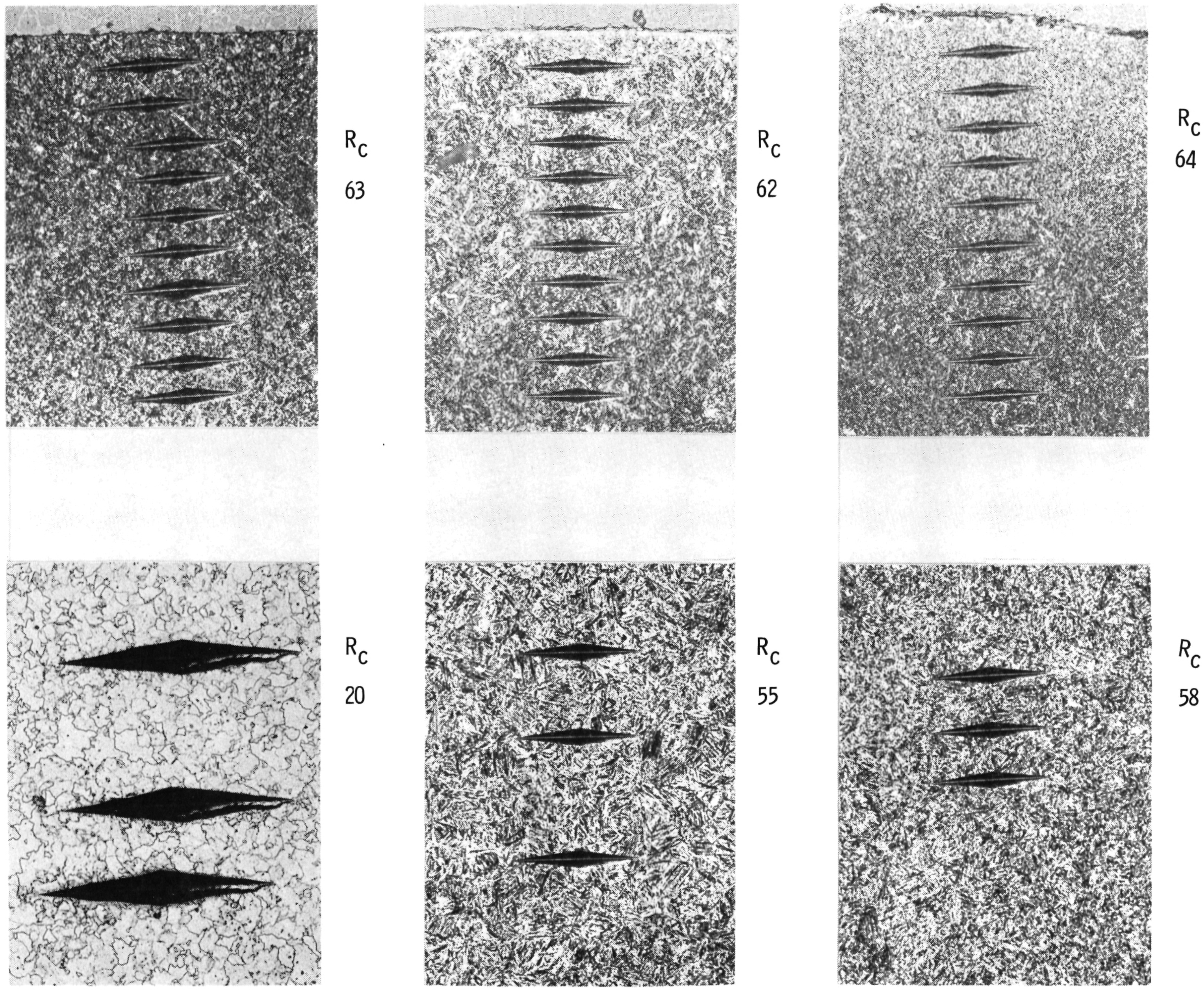


Figure 6. - Forging crack of hot forged powder metal AISI 4620 gear tooth.



(a) AISI 4620. (b) AISI 4640. (c) AISI 4340.

Figure 7. - Case and core hardness for carburized and hardened hot forged powder metal AISI 4620, AISI 4640, and machined AISI 4340.

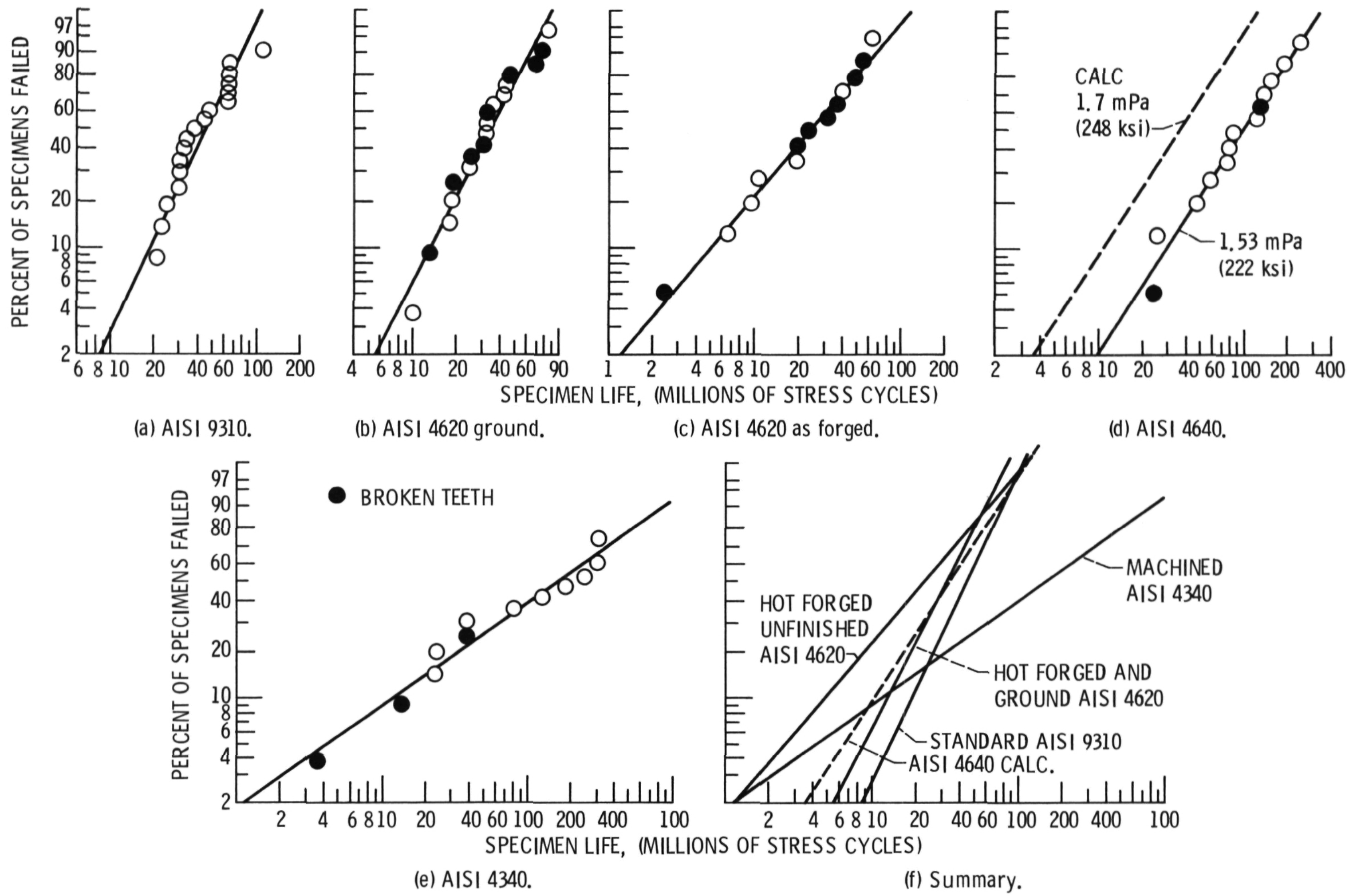
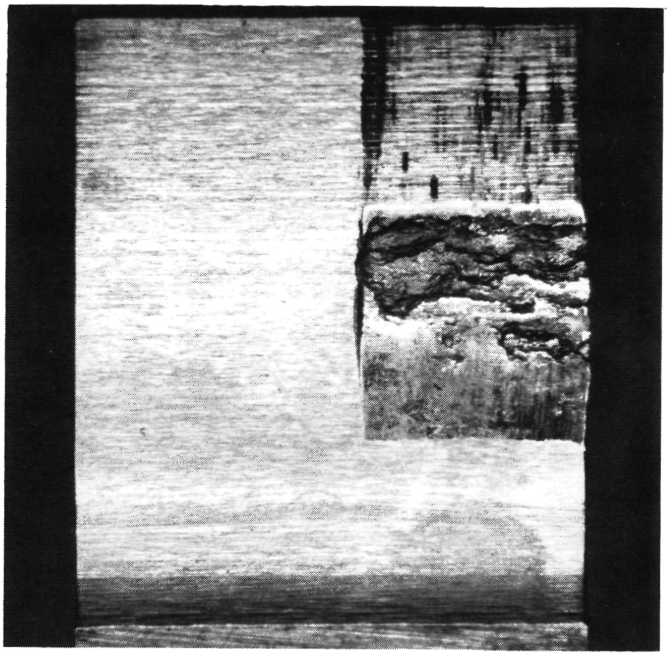
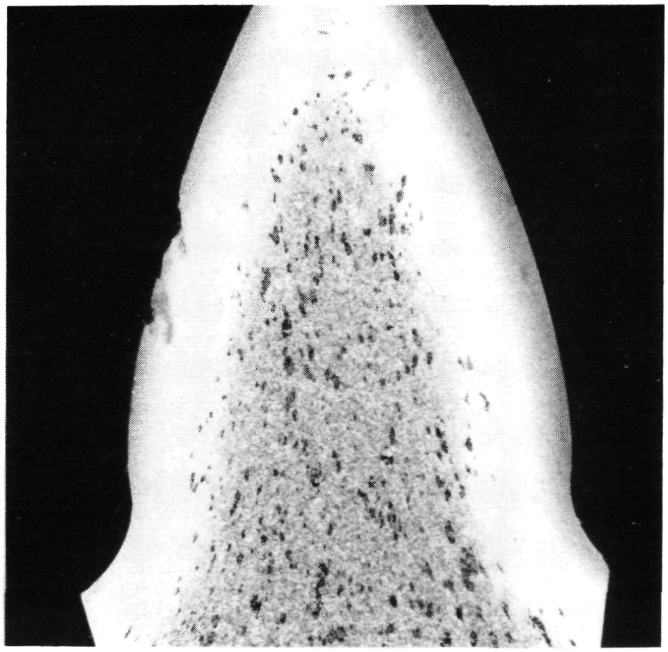


Figure 8. - Surface pitting fatigue life of machined and hot forged powder metal spur gears. Speed 10,000 rpm, temperature 350 K (170° F); maximum hertz stress 1.7 mPa (248 ksi).



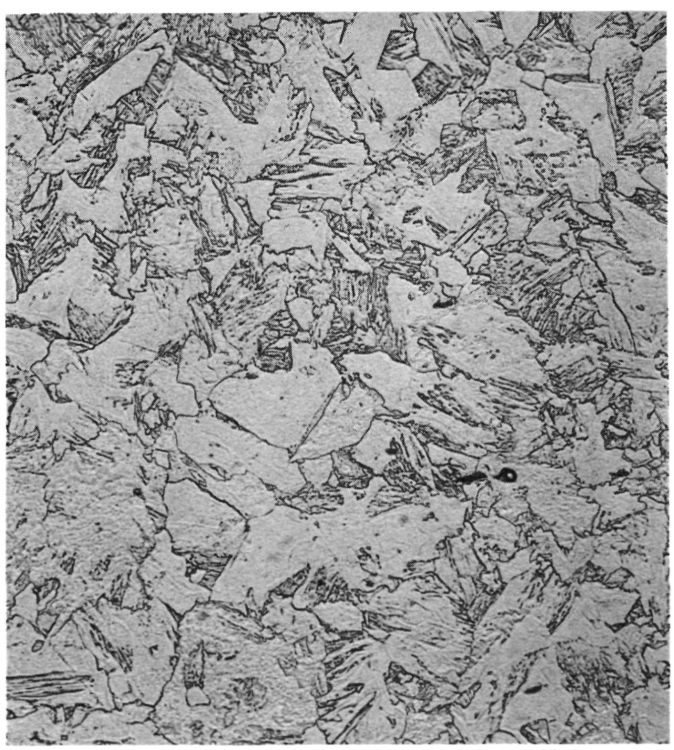
(a) Spall.



(b) Cross section.

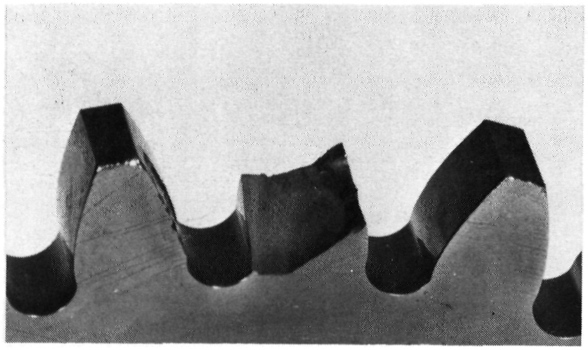
Figure 9. - Typical fatique spall for finish ground hot forged powder metal AISI 4620. Speed 10,000 RPM, temperature 350 K (170 ^{0}F): maximum hertz stress 1.7 mPa (248 kSi).

(a) Case.

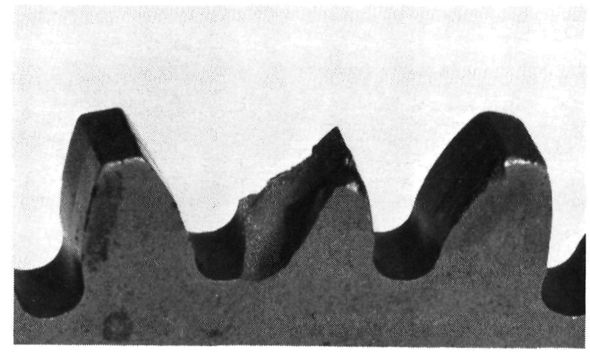


(b) Core.

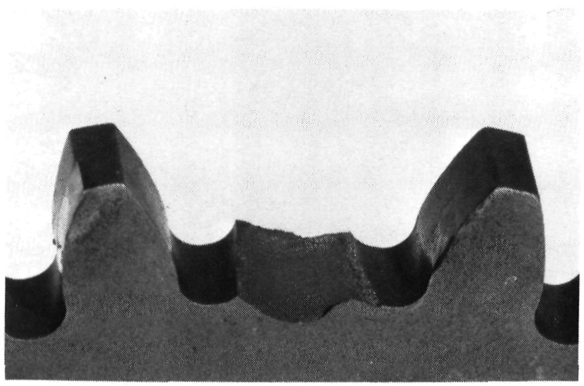
Figure 10. - Photomicrograph of hot forged case carburized and hardened powder metal AISI 4620.



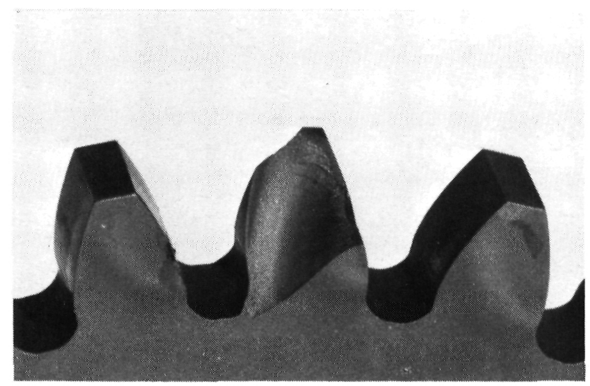
(a) AISI 4620.



(b) AISI 4640.

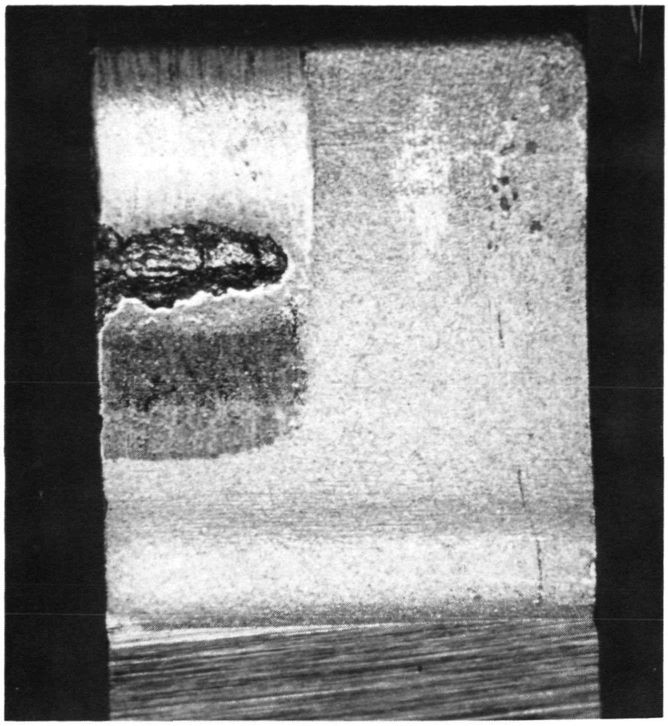


(c) AISI 4640.

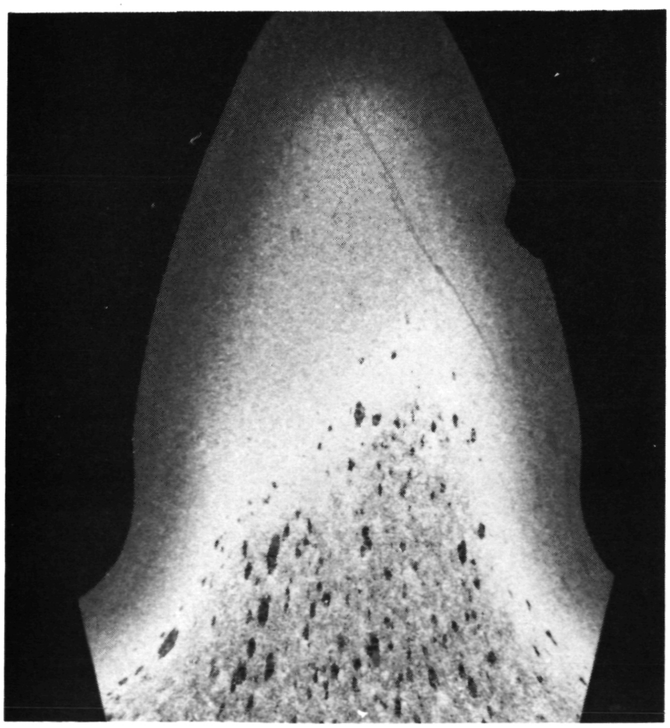


(d) AISI 4340.

Figure 11. - Tooth fractures for forged powder metal AISI 4620, AISI 4640, and machined AISI 4340. Speed 10,000 RPM, temperature 350 K (170 °F) maximum hertz stress 1.7 mPa (248 kSi) for (a) and (d), and 1.53 mPa (222 kSi) for (b) and (c).



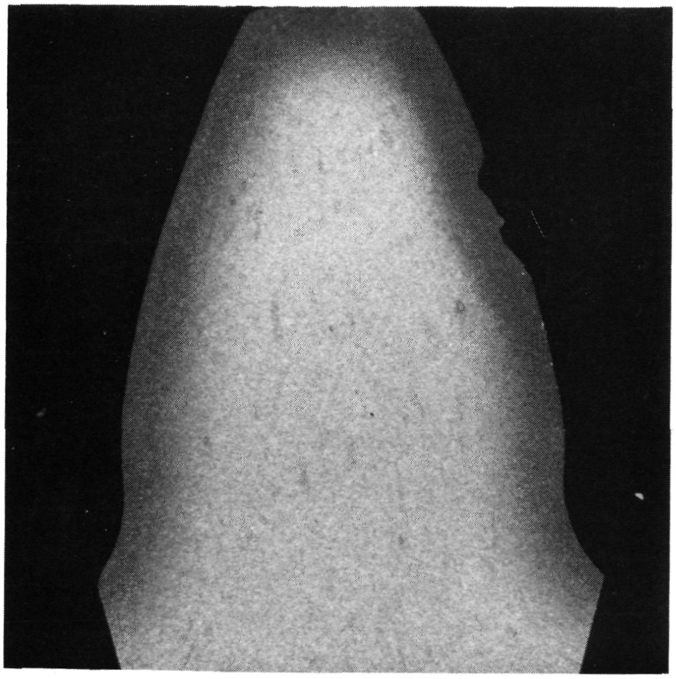
(a) Spall.



(b) Cross section.

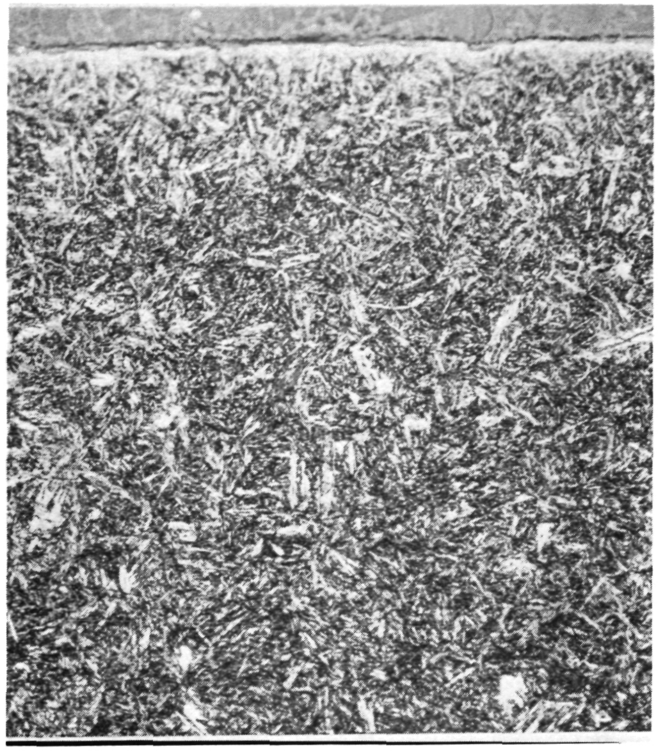
Figure 12. - Typical fatique spall for as hot forged and unfinished powder metal AISI 4620. Speed 10,000 RPM, temperature 350 K (170 ^{o}F) maximum hertz stress 1.7 mPa (248 kSi)

(a) Fatigue spall.



(b) Cross section.

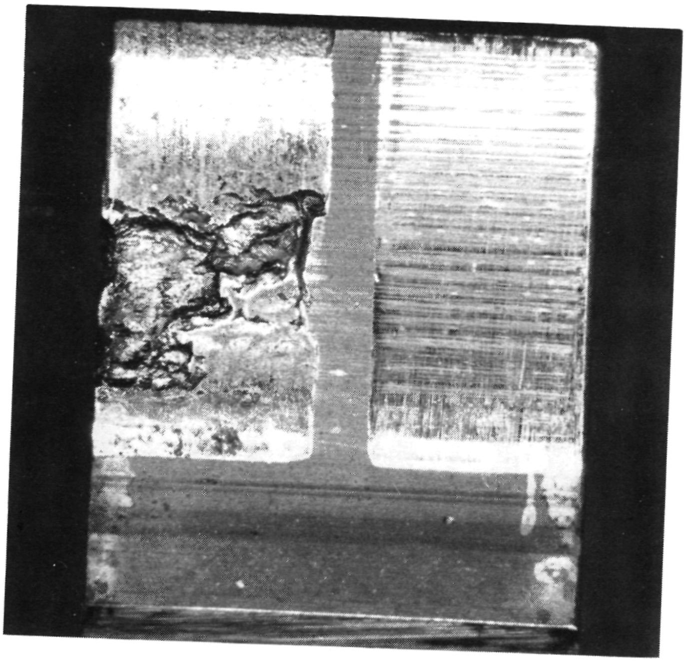
Figure 13. - Typical fatigue spall for hot forged and unfinished powder metal AISI 4640 spur gear. Speed 10,000 RPM, temperature 350 K (170 ^{o}F) maximum hertz stress 1.53 gPa (222 kSi).



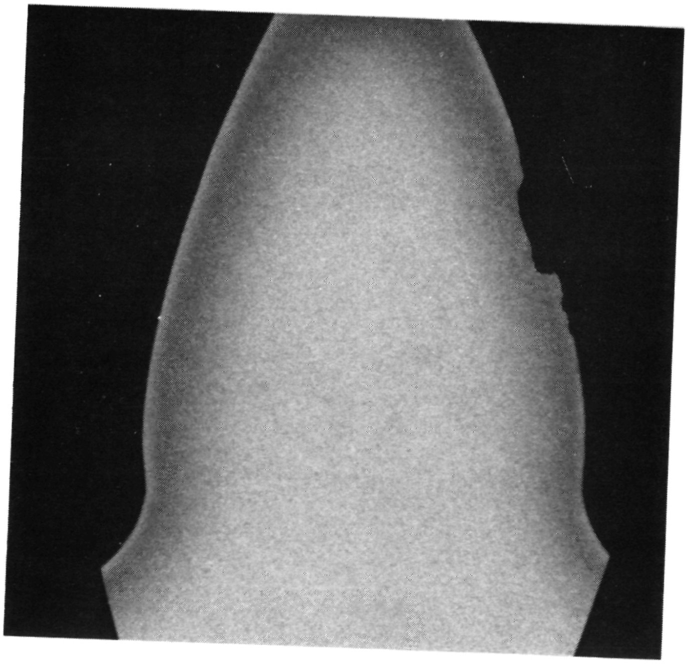
(a) Case.

(b) Core.

Figure 14. - Photomicrographs of hot forged case carburized and hardened powder metal AISI 4640.

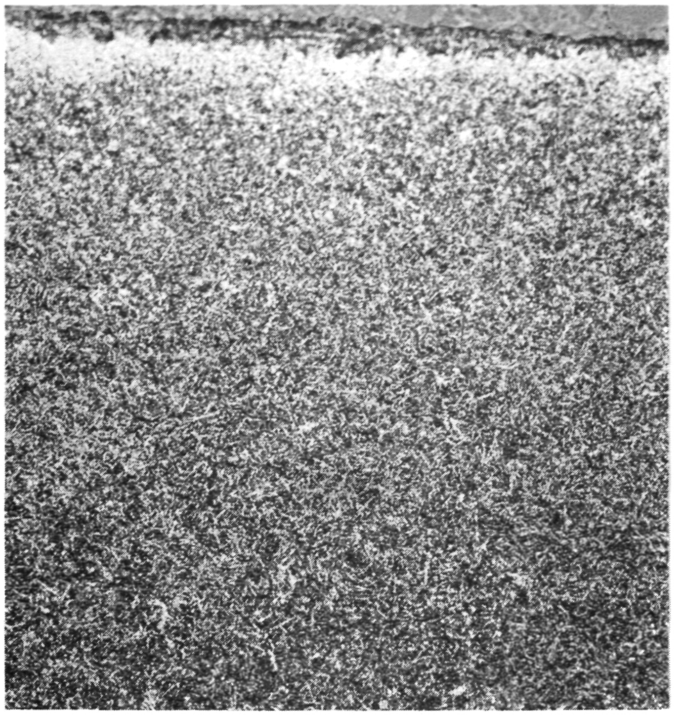


(a) Fatigue spall.



(b) Cross section.

Figure 15. - Typical fatigue spall for machined AISI 4340 spur gears. Speed 10,000 RPM, temperature 350 K (170 ^{0}F) maximum hertz stress 1.7 mPa (248 kSi).



(a) Case.

(b) Core.

Figure 16. - Photomicrographs of case and core of machined carburized and hardened AISI 4340.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-87330		

4. Title and Subtitle	5. Report Date
Surface Fatigue and Failure Characteristics of Hot Forged Powder Metal AISI 4620, AISI 4640, and Machined AISI 4340 Steel Spur Gears	
	6. Performing Organization Code 505-62-51
7. Author(s) Dennis P. Townsend	8. Performing Organization Report No. E-3024
	10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 1986 Annual Meeting of the American Society of Lubrication Engineers, Toronto, Canada, May 12-15, 1986.

16. Abstract

Spur gear surface fatigue endurance tests were conducted to investigate hot forged powder metal AISI 4620 and 4640 steel for use as a gear material, to determine endurance characteristics and to compare the results with machined AISI 4340 and 9310 steel gear materials. The as-forged and unground AISI 4620 gear exhibited a 10 percent fatigue life that was approximately one-fourth of that for AISI 9310 and less than one-half that for the AISI 4340 gears. The forged and finish ground AISI 4620 gears exhibited a 10 percent life approximately 70 percent that of AISI 9310 and slightly better than that of AISI 4340. The AISI 4640 hot forged gears had less fracture toughness and slightly less fatigue life than the AISI 4620 test gears.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Surface fatigue; Spur gears; Hot forged powder metal AISI 4620; AISI 4640	Unclassified - unlimited STAR Category 37

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified		

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