NASA TECHNICAL NOTE

NASA TN D-7535

NASA TN D-7535

EFFECT OF TIP RELIEF ON ENDURANCE CHARACTERISTICS OF SUPER-NITRALLOY AND AISI M-50 SPUR GEARS

by Dennis P. Townsend and Erwin V. Zaretsky

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1974

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TN D-7535		
4. Title and Subtitle EFFECT OF TIP RELIEF ON ENDURANCE CHARACTERISTICS OF SUPER-NITRALLOY AND AISI M-50 SPUR GEARS		5. Report Date February 1974 6. Performing Organization Code
7. Author(s) Dennis P. Townsend and Erwin V. Zaretsky		8. Performing Organization Report No. E-7414
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 501-24 11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		13. Type of Report and Period Covered Technical Note 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Tests were conducted with two groups of 8.89-centimeter (3.5-in.) pitch diameter spur gears with standard 20° involute profile with tip relief made of CVM Super-Nitralloy (5Ni-2Al) and CVM AISI M-50 at a temperature of 350 K (170° F). Super-Nitralloy gears with tip relief had a life 150 percent that of gears without tip relief. An increased scoring phenomenon was noted with the Super-Nitralloy gears with tip relief. Through-hardened AISI M-50 gears with tip relief failed due to tooth fracture. AISI M-50 gears without tip relief had a life approximately 40 times greater than the AISI M-50 gears with tip relief.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Spur gears; Super-Nitralloy; Fatigue life; Tip relief; AISI M-50	Unclassified - unlimited Cat. 15

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

* For sale by the National Technical Information Service, Springfield, Virginia 22151

EFFECT OF TIP RELIEF ON ENDURANCE CHARACTERISTICS OF SUPER-NITRALLOY AND AISI M-50 SPUR GEARS

by Dennis P. Townsend and Erwin V. Zaretsky

Lewis Research Center

SUMMARY

Tests were conducted with two groups of 8.89-centimeter (3.5-in.) pitch diameter spur gears with standard 20° involute profile with tip relief made of consumable-electrode vacuum-melted (CVM) Super-Nitralloy (5Ni-2Al) and CVM AISI M-50 at a temperature of 350 K (170° F), a maximum Hertz stress of 190×10^{7} newtons per square meter (275 000 psi), and a speed of 10 000 rpm. Tip relief was 0.001 to 0.0015 centimeter (0.0004 to 0.0006 in.) starting at the last 30 percent of the active profile. The lubricant was a super-refined naphthenic mineral oil with an additive package. Test results were compared with gears having a standard profile made of the same material and run under the same conditions.

The Super-Nitralloy gears with tip relief had a life 150 percent that of the gears without tip relief. However, the difference in life was not considered statistically significant. An increased number of scoring failures was noted with the Super-Nitralloy gears with tip relief over those Super-Nitralloy gears without tip relief.

Through-hardened AISI M-50 gears with tip relief failed due to tooth fracture. In contrast, the AISI M-50 gears having the conventional profile without tip relief run in a previous study under identical conditions failed due to surface fatigue spalling. The life of the AISI M-50 gears without tip relief had a life approximately 40 times greater than the AISI M-50 gears with tip relief under the test conditions reported.

INTRODUCTION

There is an increasing need in high-performance aircraft for increased power density and power to weight ratio. This is especially true in vertical takeoff and landing (VTOL), short takeoff and landing (STOL), and geared fan type aircraft (refs. 1 and 2). In addition, increased engine Mach number and higher engine performance characteristics are causing increased temperature demands on aircraft gear materials (ref. 3).

Gears can generally fail by one of three modes: scoring or surface distress, tooth surface spalling or pitting, and/or tooth fracture (ref. 4). All of these failure modes would be affected by increased power input into an aircraft power transmission system. That is, the reliability and expected life of the system would be reduced. This is especially true for systems with increased power density.

One means of reducing the scoring or surface distress mode of failure is by modifying the conventional involute gear profile by a method called "tip relief" (ref. 5). This method is performed by removing a small amount of metal from the profile in the addendum region of the gear teeth. As a result, the load is reduced at the end point of tooth contact at the addendum where high sliding takes place. Tip relief will also change the load pattern near the pitch line. The amount of tip relief can vary and is usually determined by the amount of tooth deflection (refs. 6 and 7). Tip relief also results in a smoother engagement of the contacting teeth.

The objective of the research reported herein was to compare under closely controlled and identical speed, load, and lubrication conditions the fatigue lives and failure modes of spur gears with and without tip relief made from two potentially high-temperature gear materials.

Endurance tests were conducted with two groups of spur gears made of consumable-electrode vacuum-melted (CVM) Super-Nitralloy (5Ni-2Al) and CVM AISI M-50. Gear specifications were an 8.89-centimeter (3.5-in.) pitch diameter and a standard 20° involute profile with tip relief. Tests were conducted at 350 K (170° F) with a maximum contact (Hertz) stress of 190×10^{7} newtons per square meter (275 000 psi) and a speed of 10 000 rpm. The results were compared with those on spur gears reported in reference 8. All experimental results reported herein and in reference 8 were obtained with the same batch of super-refined naphthenic mineral oil having an antiwear additive package. All gears of each material reported herein and in reference 8 were manufactured from a single lot of material.

APPARATUS, SPECIMENS, AND PROCEDURE

Gear Test Appartus

The gear fatigue tests were performed in the NASA Lewis Research Center's gear test appartus (fig. 1). 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 1(b). Oil pressure and leakage flow are supplied to the load vanes through a shaft seal. As the oil pressure is increased on the load vanes inside the slave gear, torque is applied to the shaft. This torque is transmitted through the test gears back to the slave gear, where an equal but opposite torque is maintained by the oil pressure. This torque on the test gears, which depends on the hydraulic pressure applied to the load vanes, loads the gear teeth to the desired stress level. The two identical test gears can be started under no load, and the load can be applied gradually, without changing the running track on the gear teeth.

Separate lubrication systems are provided for the test gears and the main gearbox. The two lubricant systems are separated at the gearbox shafts by pressurized labyrinth seals. Nitrogen was the seal gas. The test gear lubricant is filtered through a 5-micron 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 test rig is belt driven and can be operated at several fixed speeds by changing pulleys. The operating speed for the tests reported herein was 10 000 rpm.

Test Lubricant

All tests were conducted with a single batch of super-refined naphthenic mineral oil lubricant having proprietary additives (antiwear, antioxidant, and antifoam). The physical properties of this lubricant are summarized in table I. Five percent of an extreme pressure additive, designated Anglamol 81 (partial chemical analysis given in table II), was added to the lubricant. The lubricant flow rate was held constant at 800 cubic centimeters per minute, and lubrication was supplied to the inlet mesh of the gear set by jet lubrication. The lubricant inlet temperature was constant at 319±6 K ($115^{\circ}\pm10^{\circ}$ F), and the lubricant outlet temperature was nearly constant at 350±3 K ($170^{\circ}\pm5^{\circ}$ 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 also reduced the effect of the oil additives on the gear surface boundary lubrication by reducing the chemical reactivity of the additive-metal system by excluding oxygen (ref. 9).

Test Gears and Materials

The test gears were manufactured from two materials. These were CVM Super-Nitralloy (5Ni-2Al) and CVM AISI M-50 steel. The chemical composition of these materials is given in table III. Super-Nitralloy (5Ni-2Al) is an advanced material which has been used in aircraft gear applications. This material, which has shown good gear load carrying capacity (ref. 10), is similar to Nitralloy N except for the addition of 2 percent nickel and 1 percent aluminum to give it better hot hardness capability and better nitriding capability. The Nitralloy N material has been used for aircraft gears and splines for many years and was used for high-temperature lubricant testing in references 11 and 12. Bending fatigue tests (ref. 10) of Super-Nitralloy (5Ni-2Al) gear teeth indicate that this material has very good strength properties at temperatures to 644 K (700° F).

AISI M-50 steel has been used mainly as a bearing steel. However, there has been limited application of this material for gears in aircraft accessory gear boxes. This material has an operating temperature potential in excess of 589 K (600° F) (refs. 13 and 14).

Dimensions for the test gears are given in table IV. All gears has a nominal surface finish on the tooth face of 0.406 micrometer (16μin.) rms and a standard 20° involute tooth profile with tip relief. Tip relief was 0.001 to 0.0015 centimeter (0.0004 to 0.0006 in.) starting at the last 30 percent of the active profile. Figure 2 illustrates the difference between a conventional gear tooth and that with tip relief.

The gears manufactured from the CVM AISI M-50 material were through hardened to a Rockwell C hardness of 62±1 in accordance with the heat-treatment schedule of table V. Figure 3 is a photomicrograph of an etched and polished surface showing the microstructure of the AISI M-50 material. The carbide cluster apparent in the micrograph indicates that the M-50 material perhaps was not worked enough to break up the carbide formations. A condition such as this may have some adverse effect on fatigue life (ref. 15).

The gears manufactured from the CVM Super-Nitralloy (5Ni-2Al) material were nitrided to a Rockwell C hardness of 61.5±1, at a case depth of 0.046 to 0.061 centimeter (0.018 to 0.024 in.), with a maximum white layer of 0.0013 centimeter (0.0005 in.). The core hardness was Rockwell C 44±1.

Photomicrographs of etched and polished surfaces showing the microstructure of the Super-Nitralloy material are presented in figure 4. The white layer (fig. 4(a)), iron nitride, forms during the nitriding process. By proper control of the nitriding conditions, the depth of the white layer can be kept to a minimum.

The Super-Nitralloy gears were heat treated in accordance with the schedule of table V. The gears were ground after nitriding to the same surface finish as the M-50 gears.

GEAR LOADING

Test Procedure

The test gears were cleaned to remove the preservative and then assembled on the test rig. The test gears were run in an offset condition with a 0.28-centimeter (0.110 in.) tooth-surface overlap to give a load surface on the gear face of 0.25 centimeter (0.100 in.) of the 0.635-centimeter (0.250 in.) wide gear, thereby allowing for 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 load of 2713 newtons per centimeter (1550 lb/in.) for 1 hour. The load was then increased to 7525 newtons per centimeter (4300 lb/in.) with a 190×10^{7} newton per square meter (275 000 psi) pitch-line Hertz stress. At the pitch-line load the tooth bending stress was 27.6×10^{8} newtons per square meter (40 000 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 35×10^{8} newtons per square meter (50 700 psi). This bending stress does not consider the effects of tip relief which will also increase the bending stress.

The test gears were operated at 10 000 rpm, which gave a pitch-line velocity of 46.55 meters per second (9163 ft/min). Lubricant was supplied to the inlet mesh at 800 cubic centimeters per minute at 319 ± 6 K ($115\pm10^{\circ}$ F). The tests were continued 24 hours a day until they were shut down automatically by the vibration-dectection transducer located on the gearbox, adjacent to the test gears. The lubricant was circulated through a 5-micron fiber-glass 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.

The pitch-line elastohydrodynamic (EHD) film thickness was calculated by the method of reference 16. It was assumed, for this film thickness calculation, that the gear temperature at the pitch line was equal to the outlet oil temperature and that the inlet oil temperature to the contact zone was equal to the gear temperature, even though the oil inlet temperature was considerably lower. It is 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 0.65 micrometer (26 μ in.), which gave a ratio of film thickness to composite surface roughness (h/σ) of 1.13.

Results and Discussion

Two groups of gears made from consumable-electrode vacuum-melted (CVM) Super-Nitralloy (5Ni-2Al) and CVM AISI M-50 were tested under a load of 7525 newtons per centimeter (4300 lb/in.), which produced a maximum Hertz stress at the pitch line of 190×10^7 newtons per square meter (275 000 psi). The gears were manufactured with tip relief. A super-refined naphthenic mineral oil was the lubricant. Failure of the gears occurred due to surface fatigue pitting, tooth breakage, or scoring. Test results were statistically evaluated using the methods of reference 17. The results were compared with data previously obtained with gears of the same materials but having a conventional (involute) tooth profile without tip relief. For purposes of evaluation, a pair of mating gears was considered as one test.

Super-Nitralloy (5Ni-2Al). - The results of testing Super-Nitralloy gears with tip relief are shown in figure 5. These results plotted on Weibull coordinates represent those gears which failed due to surface (pitting) fatigue. Weibull coordinates are the log-log of the reciprocal of the probability of survival graduated as the statisical percent of specimens failed (ordinate) against the log of time to failure or system life (abscissa). For comparative purposes, the life of Super-Nitralloy gears having a conventional profile (obtained from ref. 8) are shown in figure 6. From these results, it is apparent that tip relief does not result in improved surface fatigue life at the 10-percent failure level (90-percent probability of survival).

A typical fatigue spall for the Super-Nitralloy gears is shown in figure 6. Metallurgical examination of all failures indicated that the fatigue spalls were of subsurface origin ans were initiated at the pitch circle. A cross section of a failed gear tooth is shown in the photomicrograph of figure 7. The subsurface-initiated spall is characterized by a plurality of subsurface cracks emanating below the surface and propagating into a crack network. Eventually this developed into a typical fatigue spall or pit. An unfailed gear tooth run to 52 and 105 hours is shown in figure 8.

It has been reported (ref. 5) that tip relief may improve resistance to scoring. For the conventional gears without tip relief tested in reference 8 no scoring failures occurred. However, several scoring failures occurred with the Super-Nitralloy gears tested herein. A typical scoring failure is shown in figure 9. From these results it may be concluded that, at least under some heavily loaded conditions, tip relief may increase the incidence of scoring.

The purpose of tip relief is to reduce the loading at the end point of tooth contact at the addendum where high sliding takes place (fig. 10). This also results in smoother engagement of the contacting teeth. However, the reduced loading at the end point must be accounted for at another location in the tooth contact. This location is above the pitch point in the addendum region as shown in figure 10. It is speculated that the combination of the increased loading and sliding at this location probably accounts for the tooth scoring failures. (The combination of high load and increased sliding causes increased heating. The scoring thus can be explained on the basis of a decreased elastohydrodynamic film due to increased heat generation and loading.)

AISI M-50. - For the AISI M-50 gears with tip relief, nine out of ten sets tested failed by tooth fracture. The results of these tests are shown in the Weibull plot of figure 11. The fracture fatigue life at a 90-percent probability of survival was approximately 685×10^3 revolutions (1.14 hr). This is compared to a pitting fatigue life of 27.8×10^6 revolutions (46.4 hr) for the AISI M-50 gears without tip relief (ref. 8). One of the ten sets with tip relief failed due to surface pitting after 144×10^6 revolutions (240 hr) of operating. (The surface pitting failure data point is not shown in the data of figure 11 but was weighted in the statistical analysis as a suspended test in accordance with the methods of reference 17.)

Six of the tooth fractures with the AISI M-50 gears with tip relief originated in the root region. This is shown in figure 12(a). Three tooth fractures occurred at the addendum region (fig. 12(b)). It is speculated that the cause of the tooth fracture with the tip-relieved AISI M-50 was nearly the same as that for the scoring with the Super-Nitralloy gears with tip relief. The maximum single tooth load condition was shifted further into the addendum region causing higher tooth bending stresses. The AISI M-50 material, being through hardened and thus having a less ductile core than the case-carburized Super-Nitralloy, was susceptible to bending fatigue fracture under these conditions. It thus can be concluded that tip relief can cause a greater propensity in through-hardened material to fatigue fracture.

The results for the AISI M-50 with tip relief shown in figure 11 can be compared with the results reported in reference 8 for AISI M-50 gears without tip relief. The gears of reference 8 failed by surface pitting fatigue and had a life at a 90-percent probability of survival of 27.8×10^6 revolutions (46.4 hr). This life is approximately 40 times greater than that of the AISI M-50 gears with tip relief. However, those AISI M-50 gears without tip relief that were deliberately overrun for a period of 2 hours after a fatigue spall had occurred exhibited tooth fracture due to conventional bending fatigue (ref. 8). The spall was analogous to a notch and thus acted as a stress riser.

SUMMARY OF RESULTS

Tests were conducted with two groups of 8.89-centimeter (3.5-in.) pitch diameter spur gears with standard 20° involute profile with tip relief made of consumable-electrode vacuum-melted (CVM) Super-Nitralloy (5Ni-2Al) and CVM AISI M-50 at 350 K (170° F) with a maximum Hertz stress of 190×10^7 newtons per square meter (275 000 psi) and a speed of 10 000 rpm. Tip relief was 0.001 to 0.0015 centimeter (0.0004 to 0.0006 in.)

starting at the last 30 percent of the active profile. The lubricant was a super-refined naphthenic mineral oil with an additive package. Test results were compared with gears having a standard profile made of the same material and run under the same conditions. The following results were obtained:

1. Super-Nitralloy gears with tip relief had a life 150 percent that of gears without tip relief. However, the difference in life was not considered statistically significant.

2. Increased scoring phenomenon was noted with the Super-Nitralloy gears with tip relief over those Super-Nitralloy gears without tip relief.

3. Through-hardened AISI M-50 gears with tip relief failed due to tooth fracture. In contrast, AISI M-50 gears having a conventional profile without tip relief run in a previous study under identical conditions failed due to surface fatigue spalling. The AISI M-50 gears without tip relief had a life approximately 40 times greater than the AISI M-50 gears with tip relief under the test conditions reported.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, September 11, 1973
501-24.

REFERENCES

1. Burroughs, Lester R.: Helicopter Mechanical Power Transmissions. Paper 844, Soc. Aeron. Weight Eng., May 1970.

2. Bartone, Leonard M.; and Burroughs, Lester R.: Evaluation of Advanced Gear Forging Techniques. Paper 680632, SAE, Oct. 1968.

3. Anderson, E. L.; Baber, B. B.; Beane, G. A. IV; Ku, P. M.: Gear Load Carrying Capacities of Various Lubricant Types at High Temperatures in Air and Nitrogen Atmospheres. Southwest Research Inst. (AFAPL-TR-67-15, AD-810512), Mar. 1967.

4. Dudley, Darle W.: Practical Gear Design. McGraw-Hill Book Co., Inc., 1954, p. 295.

5. Borsoff, V. N.: On the Mechanism of Gear Lubrication. J. Basic Eng., vol. 81, no. 1, Mar. 1959, pp. 79-93.

6. Hardy, Alex: An Action Analysis of Gear Teeth with Modified Lead and Profile. Paper 670050, SAE, Jan. 1967.

7. Davies, John W.: Some Design Consideration Affecting Performance and Reliability of High-Duty Spur and Helical Gearing for Aircraft. Inst. Mech. Eng., 1958, pp. 82-90.

8. Townsend, Dennis P.; Chevalier, James L.; and Zaretsky, Erwin V.: Pitting Fatigue Characteristics of AISI M-50 and Super Nitralloy Spur Gears. NASA TN D-7261, 1973.

9. Fein, R. S.; and Kreuz, K. L.: Chemistry of Boundary Lubrication of Steel by Hydrocarbons. ASLE Trans., vol. 8, no. 1, Jan. 1968, pp. 29-38.

10. Seabrook, John B.; and Dudley, Darle W.: Results of a Fifteen-Year Program of Flexural Fatigue Testing of Gear Teeth. J. Eng. Ind., vol. 86, no. 3, Aug. 1964, pp. 221-239.

11. Beane, G. A., IV; and Lawler, C. W.: Load-Carrying Capacities of Gear Lubricants of Different Chemical Classes Based on Results Obtained with WADD High-Temperature Gear Machine Used with Induction-Heated Test Gears. Southwest Research Inst. (AFAPL-TR-65-23, AD-620294), Apr. 1965.

12. Jackson, Earl G.; Muench, Charles F.; and Scott, Ernest H.: Evaluation of Gear Materials Scoring at 700 F. ASLE Trans., vol. 3, no. 1, 1960, pp. 69-82.

13. Zaretsky, Erwin V.; Anderson, William J.; and Bamberger, Eric N.: Rolling-Element Bearing Life from 400° to 600° F. NASA TN D-5002, 1969.

14. Parker, R. J.; and Zaretsky, E. V.: Rolling Element Fatigue Lives of Through-Hardened Bearing Materials. J. Lub. Tech., vol. 94, no. 2, 1972, pp. 165-173.

15. Chevalier, James L.; Zaretsky, Erwin V.; and Parker, Richard J.: A New Criterion for Predicting Rolling-Element Fatigue Lives of Through-Hardened Steels. J. Lub. Tech., vol. 95, no. 3, 1973, pp. 287-297.

16. Dowson, D.; and Higginson, G. R.: Elasto-Hydrodynamic Lubrication. Pergamon Press, 1966.

17. Johnson, Leonard G.: The Statistical Treatment of Fatigue Experiments. Elsevier Publishing Co., 1964.

TABLE I. - PROPERTIES OF SUPER-REFINED, NAPHTHENIC, MINERAL-OIL TEST LUBRICANT

Kinematic viscosity, cm^2/sec (cS), at	
266 K (20° F)	2812×10^{-2} (2812)
311 K (100° F)	73×10^{-2} (73)
372 K (210° F)	7.7×10^{-2} (7.7)
477 K (400° F)	1.6×10^{-2} (1.6)
Flash point, K (°F)	489 (420)
Autoignition temperature, K (°F)	664 (735)
Pour point, K (°F)	236 (-35)
Density at 289 K (60° F), g/cm^3	0.8899
Vapor pressure at 311 K (100° F), mm Hg (or torr)	0.01
Thermal conductivity at 311 K (100° F), J/(m)(sec)(K) (Btu/(hr)(ft)(°F))	0.04 (0.0725)
Specific heat at 311 K (100° F), J/(kg)(K) (Btu/(lb)(°F))	582 (0.450)

TABLE II. - PROPERTIES OF LUBRICANT ADDITIVE ANGLAMOL 81

Percent phosphorous by weight	0.66
Percent sulfur by weight	13.41
Specific gravity	0.982
Kinematic viscosity at 372 K (210° F), cm^2/sec (cS)	29.5×10^{-2} (29.5)

TABLE III. - CHEMICAL COMPOSITION OF

GEAR MATERIALS BY PERCENT WEIGHT

Element	Gear material	
	AISI M-50 steel	Super-Nitralloy (5Ni-2Al)
Carbon	0.85	0.24
Manganese	.28	.25
Phosphorous	.010	.005
Sulfur	.004	.003
Silicon	.23	.22
Copper	.06	-----
Chromium	4.17	.58
Molybdenum	4.23	.26
Vanadium	.97	.12
Nickel	.08	5.16
Cobalt	.03	-----
Tungsten	.08	-----
Aluminum	-----	2.06
Iron	Balance	Balance

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)
Tip relief, cm (in.)	0.001 to 0.0015 (0.0004 to 0.0006)

TABLE V. - HEAT-TREATMENT PROCESS FOR AISI CVM

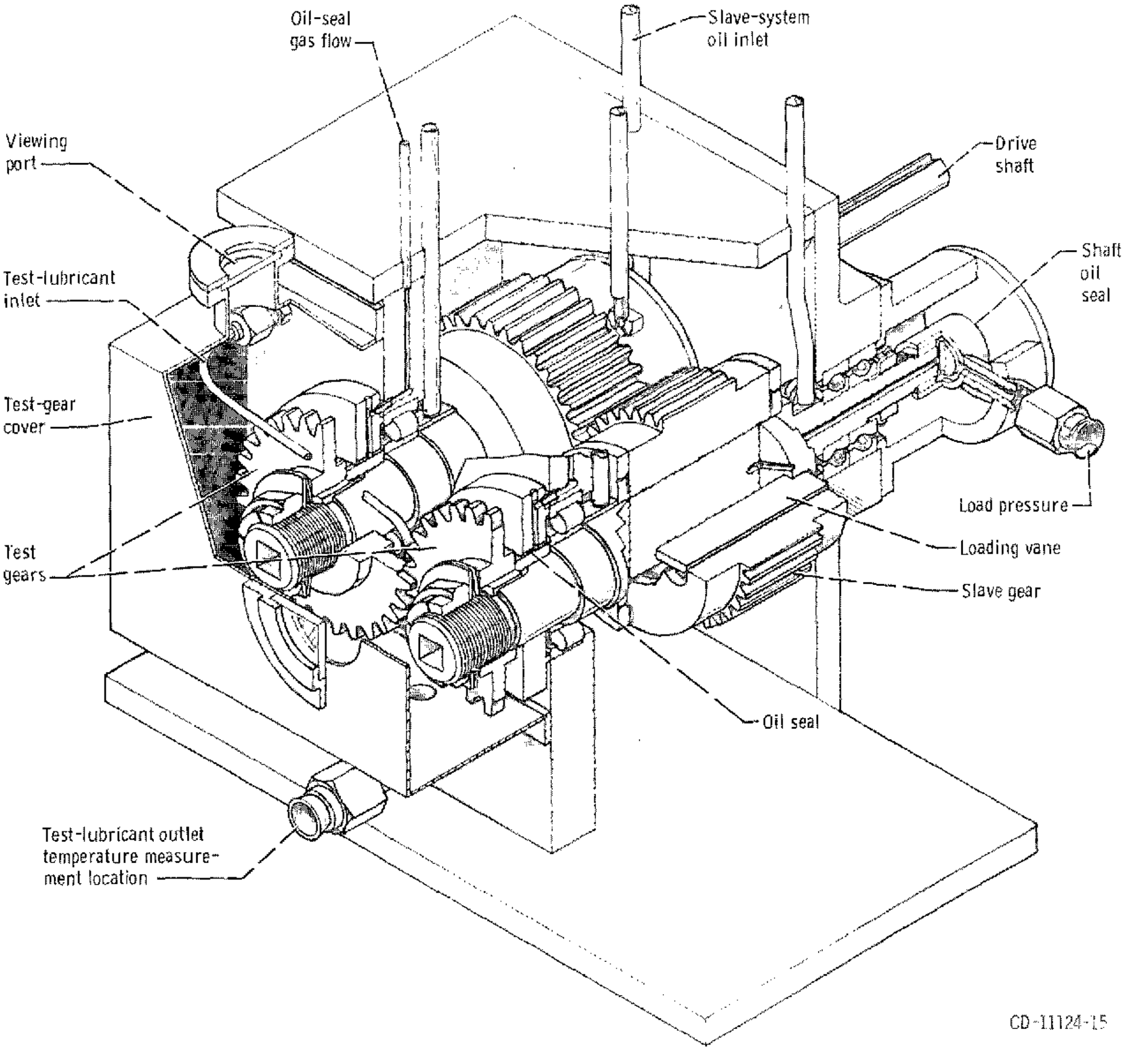
M-50 STEEL AND CVM SUPER-NITRALLOY GEARS

(a) CVM Super-Nitralloy (5Ni-2Al)

Step	Process	Temperature, K (^{o}F)	Time, hr
1	Normalize	1200 (1700)	4
2	Rough machine	----------	----
3	Copper plate	----------	----
4	Austenitize	1172 (1650)	2.5
5	Oil quench	----------	----
6	Temper to Rockwell C 30 to 36	690 (1275)	5
7	Strip copper	----------	----
8	Semifinish machining	----------	----
9	Copper plate	----------	----
10	Stress relieve	950 (1250)	2
11	Strip copper	----------	----
12	Nitride:	797-811 (975 to 1000)	60
	Case depth, 0.046 to 0.061 cm (0.018 to 0.024 in.)		
	Case hardness, Rockwell C 61.5		
	Core hardness, Rockwell C 44		

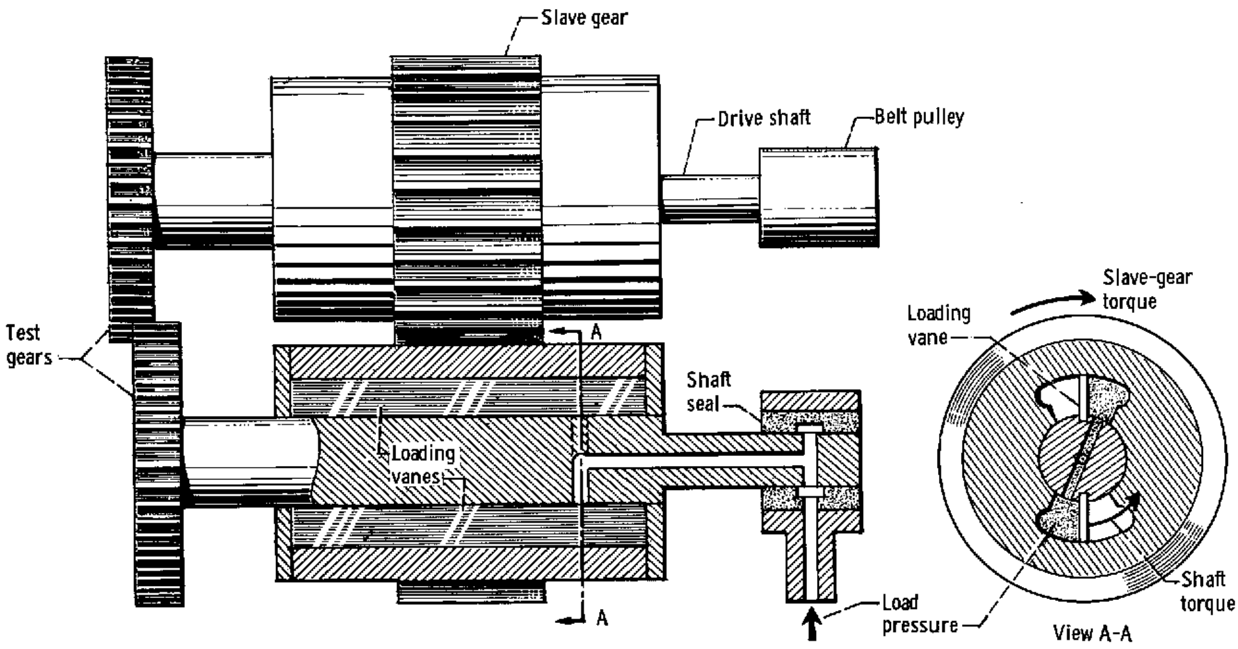
(b) CVM AISI M-50 steel

Step	Process	Temperature, K (^{o}F)	Time, hr
Preliminary heat treatment after rough machining			
1	Austenitize	1117 (1550)	0.5
2	Air cool to Rockwell C 26 to 32	----------	----
3	Copper plate all over	----------	----
Final heat treatment			
4	Preheat in neutral salt bath	1075 (1475)	0.5
5	Transfer to neutral salt bath	1395 (2050)	0.5
6	Quench neutral salt bath	839 (1050)	5
7	Air cool	311 to 339 (100 to 150)	----
8	Temper	839 (1050)	2
9	Deep freeze	172 (-120)	2
10	Retemper	839 (1050)	2



(a) Cutaway view.

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



(b) Schematic diagram.

CD-11421-15

Figure 1. - Concluded.

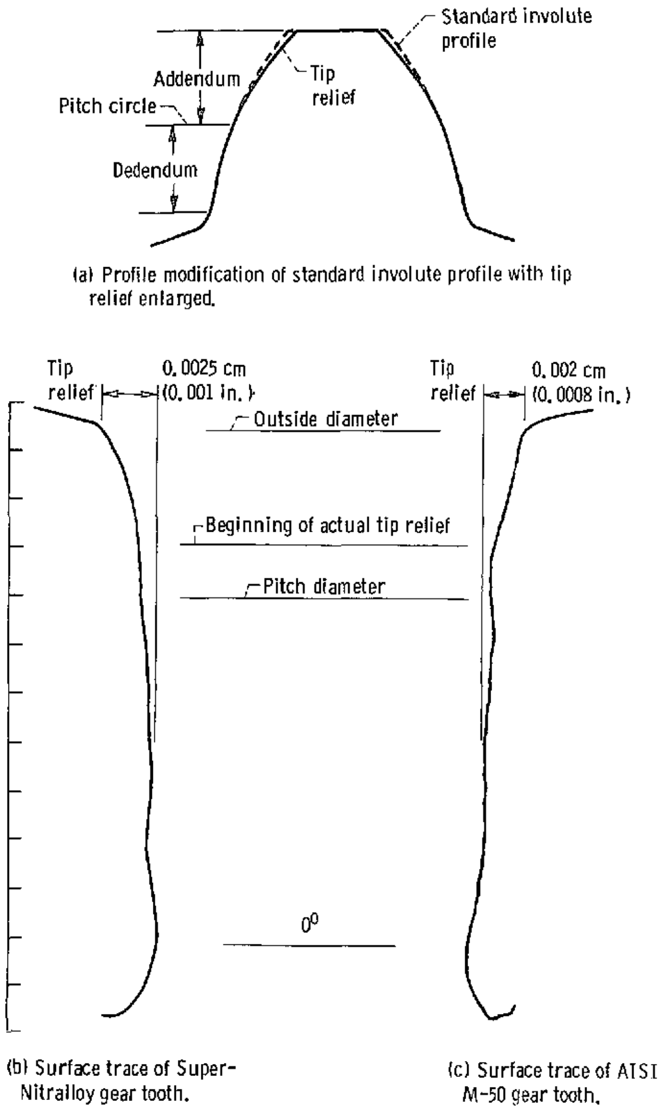


Figure 2. - Involute profile deviation for Super-Nitralloy and AIAI M-50 spur gear teeth with tip relief. Part of relief indicated (~0.0003 cm (0.0002 in.)) is deviation in pressure angle. Straight line in surface trace indicates perfect involute profile.

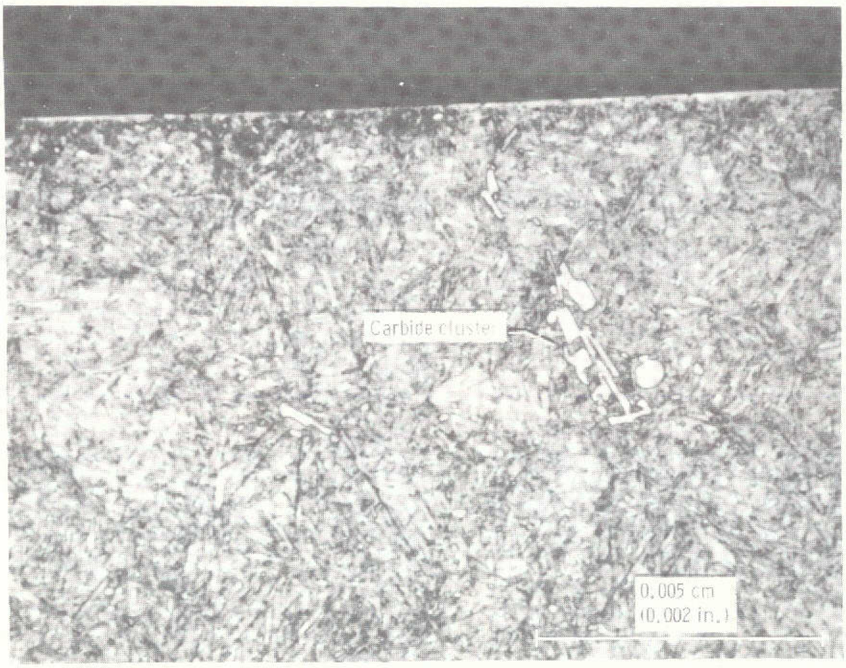
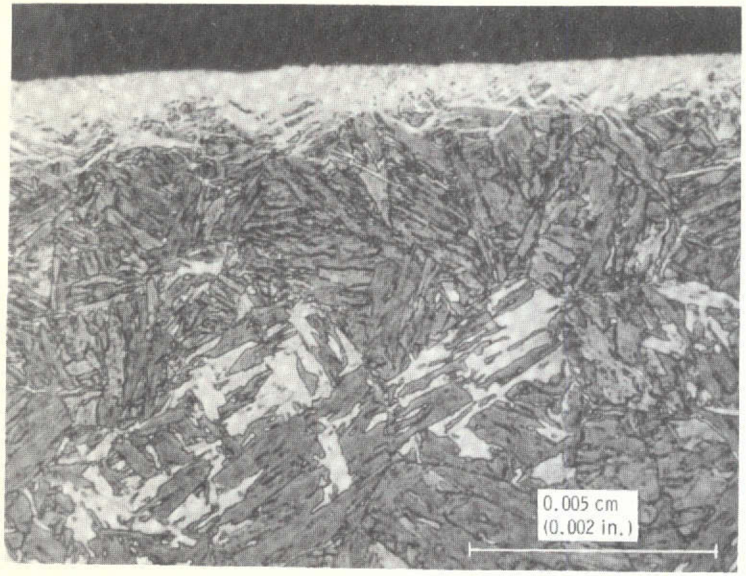
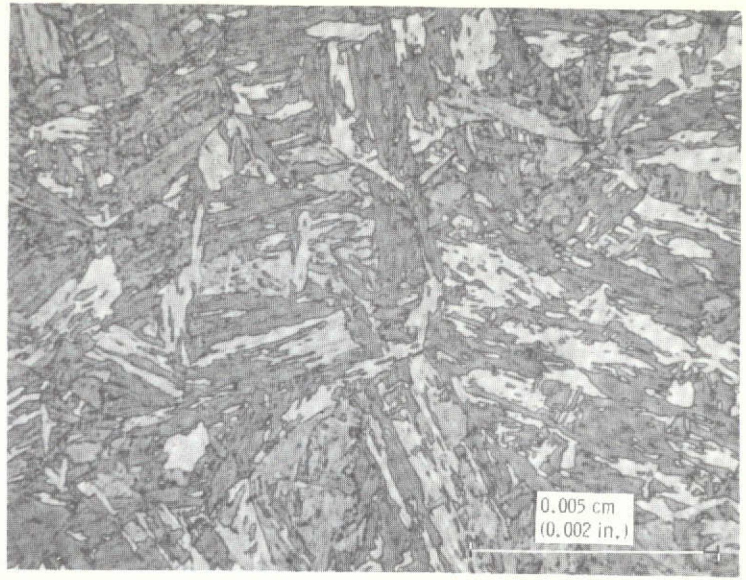


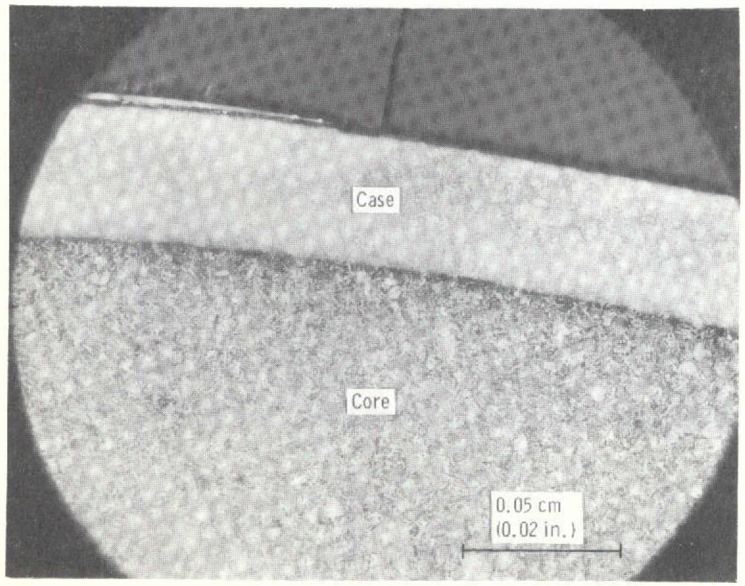
Figure 3. - Photomicrograph of etched and polished surface of AISI M-50 steel.



(a) Case.



(b) Core.



(c) Case and core.

Figure 4. - Photomicrographs of etched and polished surfaces of Super-Nitralloy (5Ni-2Al).

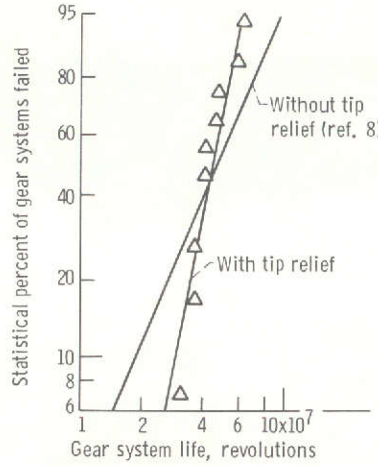


Figure 5. - Pitting fatigue lives of spur gear systems made of CVM Super-Nitralloy (5Ni-2Al) with and without tip relief. Maximum Hertz stress at pitch line, 190×10^7 newtons per square meter (275 000 psi); maximum bending stress at tooth root, 35×10^8 newtons per square meter (50 700 psi) without tip relief, 38.6 newtons per square meter (56 100 psi) with tip relief; speed, 10 000 rpm; temperature, 350 K (170° F); super-refined napthenic mineral oil.

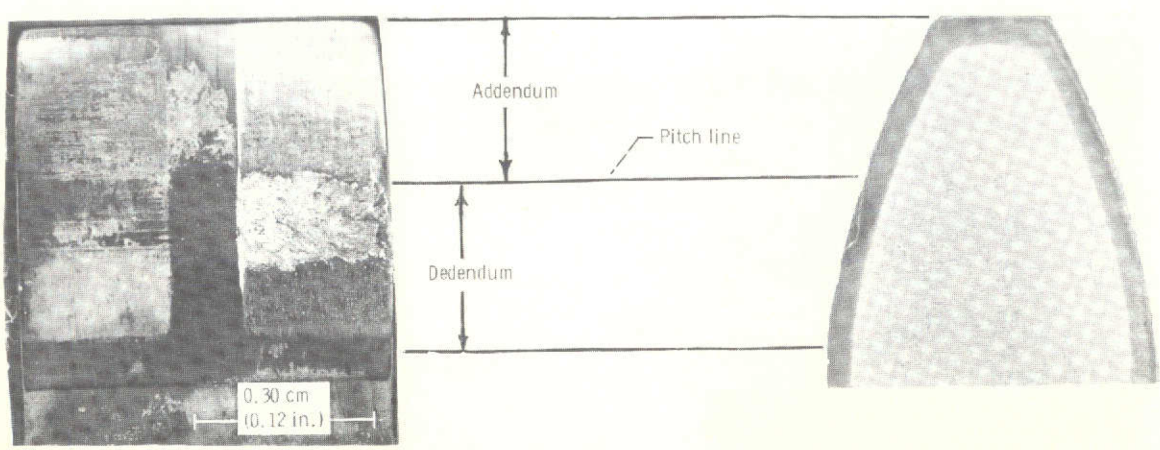


Figure 6. - Typical pitch-line fatigue spall of Super-Nitralloy (5Ni-2Al) gear with tip relief Maximum Hertz stress at pitch line, 190×10^7 newtons per square meter (275 000 psi); speed, 10 000 rpm; temperature, 350 K (170° F); lubricant, super-refined naphthenic mineral oil.

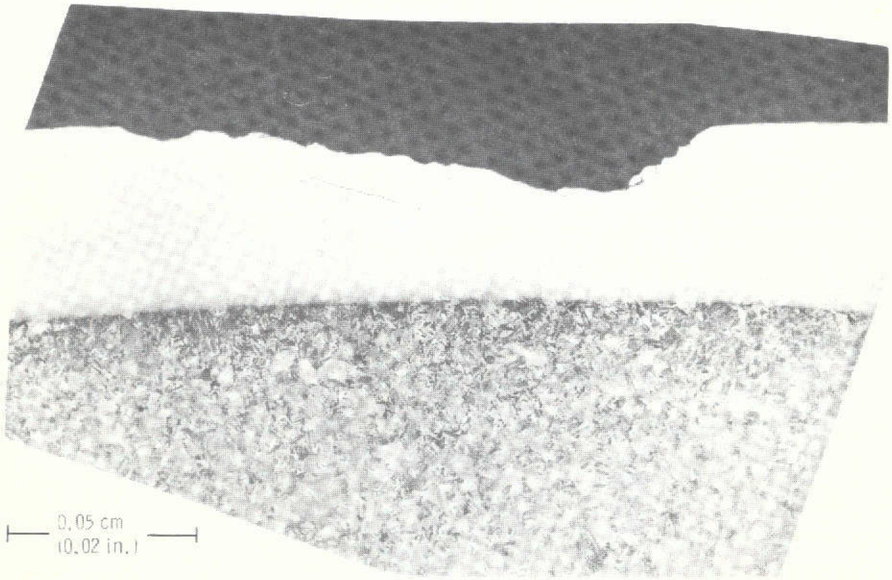


Figure 7. - Photomicrograph of pitch-line fatigue spall on Super-Nitralloy (5Ni-2Al) gear tooth with tip relief. Maximum Hertz stress at pitch line, 190×10^7 newtons per square meter (275 000 psi); speed, 10 000 rpm; temperature, 350 K (170° F); lubricant, super-refined naphthenic mineral oil.

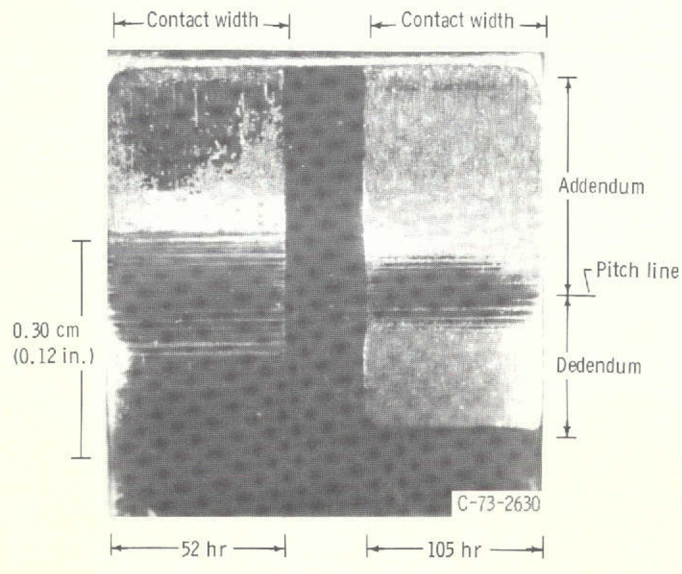


Figure 8. - Typical unfailed gear tooth with contact surfaces that have completed 52 and 105 hours. Maximum Hertz stress at pitch line, 190×10^7 newtons per square meter (275 000 psi); speed, 10 000 rpm; temperature, 350 K (170° F); lubricant, super-refined naphthenic mineral oil.

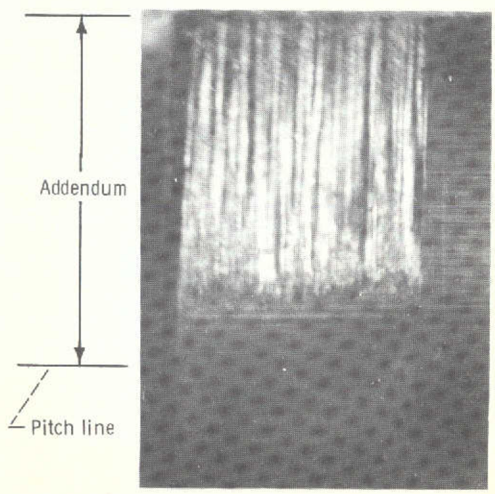
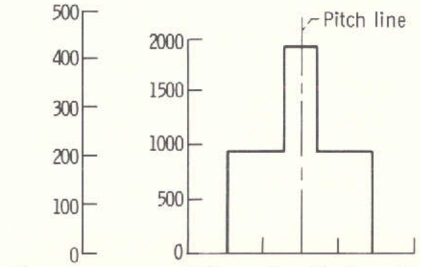
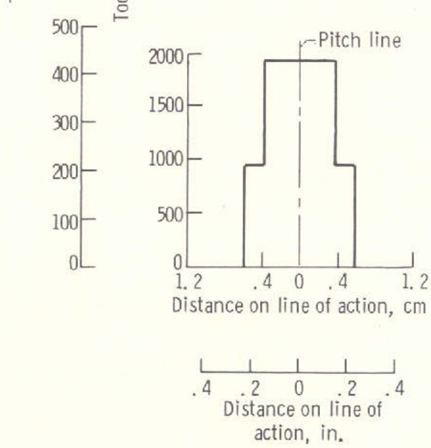


Figure 9. - Scoring failure on Super-Nitralloy gear tooth with tip relief. Maximum Hertz stress at pitch line, 190×10^7 newtons per square meter (275 000 psi); speed, 10 000 rpm; temperature, 350 K (170° F); super-refined naphthenic mineral oil.



(a) Conventional tooth profile. Maximum bending stress at tooth root, 35x10^8 newtons per square meter (50 700 psi).



(b) Excess tip relief, 12.7×10^{-4} centimeter (5×10^{-4} in.). Maximum bending stress at tooth root, 38.6 newtons per square meter (56 100 psi).

Figure 10. - Load diagram for gear tooth with excess tip relief compared to load diagram for conventional tooth profile.

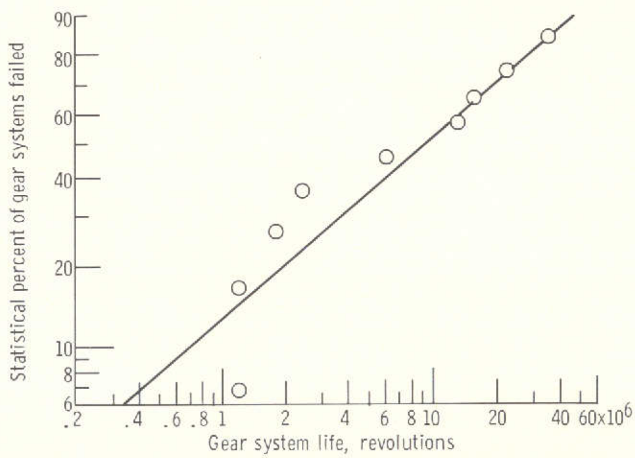
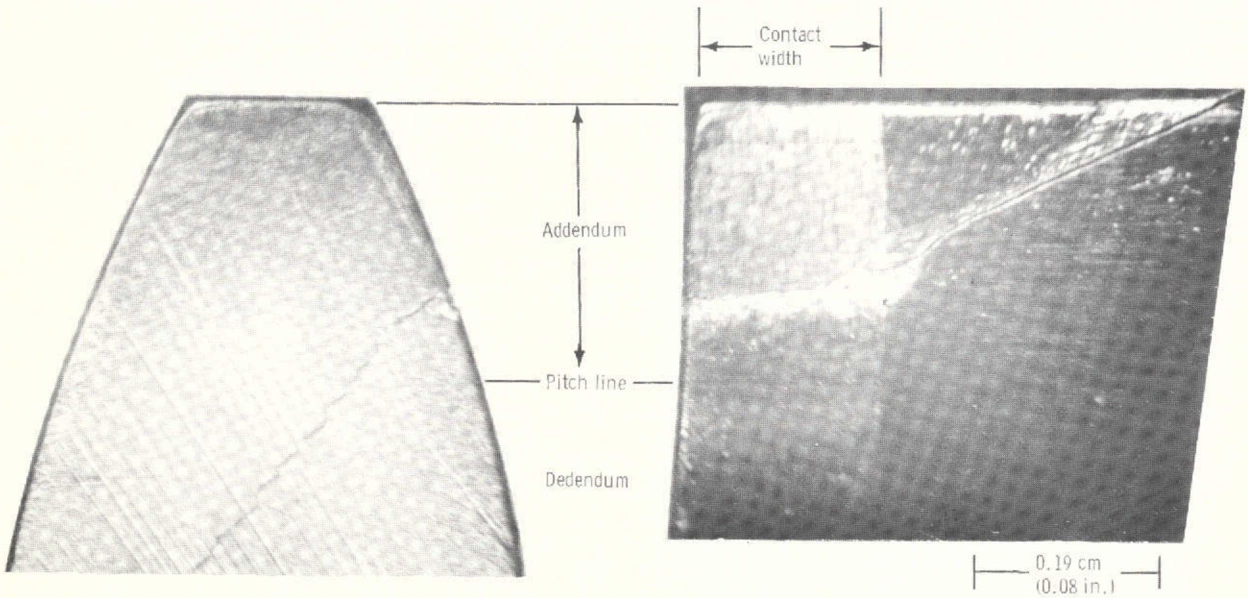
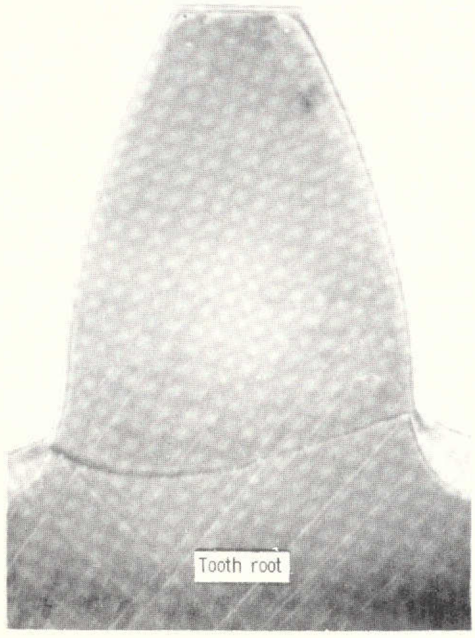


Figure 11. - Fracture fatigue life of AISI M-50 spur gear system with tip relief. Maximum Hertz stress at pitch line, 190×10^{7} newtons per square meter (275 000 psi); maximum bending stress at tooth root, 38.6 newtons per meter (56 100 psi); speed, 10 000 rpm; temperature, 350 K (170° F); lubricant, super-refined naptheric mineral oil.



(a) Tooth fracture origin in adendum.



(b) Tooth fracture origin in root.

Figure 12. - Fatigue fracture of AISI M-50 gear teeth with tip relief. Maximum Hertz stress of pitch line, 190×10^{7} newtons per square meter (275 000 psi); maximum bending stress at tooth root, 38.6 newtons per square meter (56 100 psi); speed, 10 000 rpm; temperature, 350 K (170^{0} F); lubricant, super-refined naphthenic mineral oil.

NASA-Langley, 1974 E-7414

CAT.-15