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A LIFE STUDY OF AUSFORGED, STANDARD FORGED AND STANDARD MACHINED AISI M-50 SPUR GEARS

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A LIFE STUDY OF AUSFORGED, STANDARD FORGED AND STANDARD MACHINED AISI M-50 SPUR GEARS

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ABSTRACT

Tests were conducted at 350 K (170° F) with three groups of 8.9 cm (3.5 in.) pitch diameter spur gears made of vacuum induction melted (VIM) consumable-electrode vacuum-arc melted (VAR), AISI M-50 steel and one group of vacuum-arc remelted (VAR) AISI 9310 steel. The pitting fatigue life of the standard forged and ausforged gears was approximately five times that of the VAR AISI 9310 gears and ten times that of the bending fatigue life of the standard machined VIM-VAR AISI M-50 gears run under identical conditions. There was a slight decrease in the 10-percent life of the ausforged gears from that for the standard forged gears. However, the difference is not statistically significant.

The standard machined gears failed primarily by gear tooth fracture while the forged and ausforged VIM-VAR AISI M-50 and the VAR AISI 9310 gears failed primarily by surface pitting fatigue. The ausforged gears had a slightly greater tendency to fail by tooth fracture than the standard forged gears.

INTRODUCTION

The requirements for advanced helicopter transmission and aircraft engine gearboxes include weight reduction, higher temperature operations than present day aircraft, as well as increased reliability and service life. The gearing in these aircraft is expected to carry greater loads, operate at higher temperatures because of increased engine speeds, provide improved system life, in

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addition to providing low maintenance rates and higher reliability. Elevated temperature operation of gears is also required where the transmission must operate for short periods without lubrication and cooling without resulting in a catastrophic failure. Under these operating conditions, a material such as AISI M-50 can operate to 589 K (600° F) [1].

The failure characteristics and mechanical properties must be defined in existing and potential gear materials before improvements can be made in gear material technology. Three possible approaches to improve the state-of-the-art in gear material technology can be pursued individually or simultaneously. These consist of (a) gear life testing coupled with failure analysis and (b) improving gear material properties, and/or (c) exploring new or improved gear designs.

One fabrication method which has the potential to improve the strength and life of gear teeth is termed "ausforging". Ausforging is a thermomechanical metal working process whereby a steel is forged or otherwise worked while it is in the meta-stable austenitic condition [2]. A number of researchers have investigated this process [3-6]. The application of ausforging to machine elements such as rolling-element bearings was first reported in [7].

The results of tests on AISI M-50 rolling-element bearings having components ausforged to an 80-percent deformation showed that these parts had a pitting fatigue life approximately ten times greater than that obtained with the same bearing made from conventional AISI M-50 material [7]. Similar results were obtained in [8] with 35-mm bore single row radial ball bearings. Some of the ausformed balls produced for the latter bearings were independently evaluated and the results reported in [9]. These results also indicate a significant improvement in fatigue life over conventional AISI M-50 balls. In addition, work was performed with large diameter ausforged bearings [10] which further demonstrated the potential life improvement with this process. While ausforging is a highly sophisticated metal-working procedure, in respect to gears another more readily available (and less expensive) method consists of utilizing standard forging techniques and integrally forming the gear teeth with the hub. The advantage here is the excellent root grain-flow pattern, which should be conducive to improved bending fatigue strength in the critical tooth root area.

Surface fatigue tests were conducted on spur gears manufactured from standard processed AISI M-50 material [11-13]. The results of the investigation revealed that the AISI M-50 material had the potential for long life gear application. However, material being through hardened had a tendency for gear tooth fracture due to bending fatigue after extended running subsequent to a surface fatigue spall. The surface spall acted as a stress raiser leading to a tooth bending fatigue failure. Another series of tests were run with the AISI M-50 gears manufactured with tip relief. The primary failure mode with the latter gears was bending fatigue resulting in very short life gears.

The objective of the research reported herein which was based on the work reported initially in [14, 15] was to compare, under closely controlled test conditions, the fatigue lives and failure modes of test spur gears made from standard forged, ausforged and standard machined AISI M-50 steel and case carburized and hardened AISI 9310 gear steel.

APPARATUS, SPECIMENS, AND PROCEDURE

Gear Test Apparatus

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

Separate lubrication systems are provided for the test gears and the main gearbox. The two lubricant systems are separated at the gearbox shafts by pressurized labyrinth seals. Nitrogen 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 emmersion 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 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 1. Five percent of an extreme pressure additive, designated Anglamol 81 (partial chemical analysis given in Table 2), 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^{O}±10^{O} F), and the lubricant outlet temperature was nearly constant at 350±3 K (170^{O}±5^{O} F). The 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. By excluding oxygen the 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[16].

Test Gears

The standard forged and ausforged test gears were manufactured from a single lot of vacuum induction melted (VIM) consumable-electrode-vacuum-arc-remelted (VAR) AISI M-50 steel. The standard heat-treated and machined VIM-VAR AISI M-50 gears were manufactured from a single lot of material and by the same machining method as the forged and ausforged material. The chemical composition of the AISI M-50 material is given in Table 3. The heat treatment for the standard forged and standard machined M-50 gear is given in Table 4. A photomicrograph of an etched and polished standard machined AISI M-50 gear material is shown in Fig. 2(a). The AISI 9310 gears were manufactured from a single lot of vacuum arc remelted (VAR) AISI 9310. These gears were manufactured with the same profile and crown radius as the M-50 gears. The chemical composition of the AISI 9310 gears is given in Table 3. The heat treatment for the AISI 9310 gears is given in Table 5. A photomicrograph of etched and polished surface of the AISI 9310 gear is shown in Fig. 2(d).

Dimensions for the test gears are given in Table 6. All gears have a nominal surface finish on the tooth face of 0.406 micrometer (16 μ in.) rms and a standard 20° involute 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. The gears were also crowned to prevent excessive edge loading.

GEAR FORGING

Standard Forged Gears

A controlled-energy-flow forming technique (CEFF) was utilized during the normal forging of the gears. This high-velocity metal-working procedure has been a production process for several years [17, 18]. A number of iterations were required before the optimum sequence of forging was established. The actual forging sequence for the standard forged gear is shown in Table 7. The initial two forging trials resulted in considerable lack-of-fill condition at the outer-gear tooth periphery. This condition was remedied by increasing the volume of the forging preform and increasing the forging temperature from 1367 to 1395 K (2000° to 2050° F). Dimensional measurements of parts after the fourth forging trial showed the parts to be nearly perfect except that they did not have the required 0.25 to 0.38 mm (0.010 to 0.015 in.) of excess material required for final machining. After a final modification, dimensionally acceptable gear forgings were produced. The die inserts for this forging are shown in Fig. 3.

Gear samples were cross sectioned and etched to study the grain-flow pattern. Fig. 4(a) shows the grain flow pattern for the standard forged gear. Fig. 2(b) is a photomicrograph of the standard forged gear structure. The hardness of the gears was Rockwell C 62-64. Metallographic examination revealed no evidence of decarburization. X-ray diffraction measurements showed the retained austenite to be less than 1 percent.

Ausforged Gears

The initial ausforging trial was performed on a controlled-energy-flow-forming machine which had a maximum energy output of 102, 000 N-M (75, 000 lb ft). This unit had been adequate for the production of the standard forged gear. However, at the lower ausforging temperature [1075 K (1475° F)] this machine did not have sufficient capacity. It was therefore decided to adapt the tooling to a larger CEFF machine with a capacity of 542, 000 N-M (400, 000 lb ft).

After several forging trials involving both tooling and procedural changes the gear shown in Fig. 5(a) was produced. The teeth however were only approximately 60 percent formed. The tooth fill condition was improved by changes in the die configuration and by slightly increasing the ausforging temperature to 1103 K (1525° F) in order to achieve improved metal flow characteristics.

The subsequent forging trials were successful and resulted in the production of dimensionally acceptable parts. These are illustrated in Fig. 5(b). The die inserts did not exhibit significant wear after 25 gear forgings. This is shown in Fig. 6. While there is some evidence of scoring and upsetting, no serious damage or tooth breakage was encountered.

The only remaining two problems encountered were (a) a heavier than expected flash area which required more time for removal during final machining. The second problem was related to the grain flow pattern of the ausforged gears (Fig. 4(b)). While the as ausforged gears had good grain flow patterns, they did not have the desirable close net tooth shape as the standard forged gears. As a result, some of the advantage of good grain flow was lost during final machining. Fig. 2(c) is a photomicrograph of the ausforged gear structure. The hardness of the gears was Rockwell C 62 to 64. The metallographic examination revealed no evidence of decarburization and the retained austenite was less than 1 percent.

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 0.030-centimeter (0.120-in.) tooth-surface overlap to give a load surface on the gear face of 0.28 centimeter (0.110 in.) of the 0.635-centimeter (0.250-in.) wide gear, thereby allowing for edge radius of the gear teeth. This offset loading causes a twisting in the gear tooth of a 1×10^{-3} radian or 2.6×10^{-4} centimeter (1.1×10^{-4} in.) deflection in the 0.28-centimeter (0.11-in.) tooth width at the highest point of single tooth contact. However, the mating tooth twists in the opposite direction approximately the same amount which, along with the crown radius, prevents edge loading.

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 1157 newtons per centimeter (661 lb/in.) for 1 hour. The load was then increased to 5784 newtons per centimeter (3305 lb/in.) with a 17.1×10^{8} newtons per square meter (248,000 psi) pitch-line Hertz stress.

At the pitch-line load, the tooth bending stress was 2.48×10^{8} newtons per square meter (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 2.67×10^{8} newtons per square meter (38,700 psi). This bending stress does not consider the effects of tip relief which will further increase the static bending stress in addition to increasing the dynamic load.

The test gear shaft deflection resulting from the overhung load gives a tooth mismatch of 1. 5×10^{-4} centimeter (6×10^{-5} in.) across the 0.28-centimeter (0.11-in.) contact face width. This amounts to approximately 10 percent of the Hertz deflection of 1. 3×10^{-3} centimeter (5×10^{-4} in.). This could cause some edge loading effects. However, the crown radius in the tooth face prevents edge loading.

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±10° F). The tests were continued 24 hours a day until they were shut down automatically by the vibration-detection 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 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 Grubin [19]. 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) or 1. 13.

RESULTS AND DISCUSSION

Three groups of AISI M-50 gears (standard forged, ausforged and standard heat-treated and machined) and one group of AISI 9310 gears were tested under a load of 5784 newtons per centimeter (3305 lb/in.) which produced a maximum Hertz stress of 17.1×10^{8} newtons per square meter (248,000 psi). The gears were manufactured with a 0.0013-centimeter (0.0005-in.) tip relief and with a crown radius to reduce edge loading effects. The lubricant was a super-refined naphthenic mineral oil with an extreme-pressure additive package. The gears failed by either surface pitting fatigue or tooth bending fracture.

Test Results

Test results were statistically evaluated using the method of [20]. For this evaluation a pair of mating gears was considered as one test.

The test results with the standard machined AISI M-50 gears are shown in Fig. 7(a). These results plotted on Weibull coordinates represent those gears that failed by bending tooth fracture. Weibull coordinates are the log-log of the reciprocal of the proability of survival graduated as the statistical percent of specimens failed (ordinate) against the log of time to failure or system life (abscissa). Of the 19 tests with the standard machined AISI M-50 gears, thirteen failed by bending tooth fracture and only six failed by surface pitting fatigue.

The results of the tests with the stnadard forged gears are shown in Fig. 7(b). These results plotted on Weibull coordinates represent those gear systems that failed by surface pitting fatigue. The 10-percent pitting fatigue life of the standard forged gears is approximately ten times that of the bending fatigue life of the standard machined gears. Two of the nineteen test gears included in this data also failed from tooth fracture after a fatigue spall had formed and only after the gears had been run for some time beyond the pitting fatigue failure.

The statistical results of the tests with the ausforged gears are shown in Fig. 7(c). These results, plotted on Weibull coordinates, represent those gears that failed by surface pitting fatigue. There is a slight decrease in the 10-percent life of the ausforged gears over that of the standard forged gears. However, this difference is not statistically significant. The ausforged gears failed primarily by surface fatigue pitting because of their increased tooth bending strength. These gears exhibited a pitting fatigue life approximately ten times the bending fatigue life of the standard machined gears.

Of the twenty-one (21) tests completed on the ausforged AISI M-50 gears, five tests resulted in gear tooth fracture; all of which were the result of prior surface fatigue spalls. These failures showed evidence of fatigue type fracture propagation.

Test results of the AISI 9310 gears [21] are shown in Fig. 7(d). By way of comparison, Fig. 7(e) is a summary Weibull plot of the three different AISI M-50 gears (machined, forged, and ausforged) along with the plot of case carburized and hardened AISI 9310 gears run under identical conditions. It can be seen that the forged and ausforged gears had approximately five times the 10-percent life of the AISI 9310 gears. The standard machined gears however had a 10-percent bending fatigue life which was only about 40 percent that of the AISI 9310 gear surface fatigue life. Since the standard forged and ausforged gears had approximately the same pitting fatigue endurance life, the added cost and complexity of producing ausforged gears would suggest that the standard forged gears are preferrable over the ausforged gear. The excellent performance of the standard forged gears with integrally forged teeth proved this to be a viable and cost effective approach to high-strength, high-temperature gearing.

Failure Analysis

A typical fatigue spall of the standard machined AISI M-50 is shown in Fig. 8(a). 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. A typical gear tooth fracture and cross section of the standard machined AISI M-50 gear is shown in Fig. 9(a). The failure originated in the root area and was not related to any prior surface fatigue spall caused by normal tooth contact as shown in the Scanning Electron Microscope (SEM) photo, Fig. 10(a). The fracture surface in Fig. 10(a) shows the dimpled fracture pattern which is typical of a tensile failure; thus, supporting the conclusion that the tooth failed in a pure bending overload mode. The failures are essentially classical root crack failures [22]. Similar results were obtained with standard machined AISI M-50 gears with tip relief in [13] at a higher tooth loading.

A typical fatigue spall of a standard forged gear is shown in Fig. 8(b). These fatigue spalls were also primarily of subsurface origin initiated at or near the pitch diameter in the region of maximum Hertz stress. A fractured tooth and a cross section of the standard forged gear is shown in Fig. 9(b). The tooth fracture originated at the location of a previous surface fatigue spall that was overrun for some time. The failure then propagated in a cyclic fatigue mode as shown by the fatigue striations in the SEM photograph [Fig. 10(b)] to a point where it transitioned to a tensile failure. This finally resulted in a total separation of the gear tooth. Fig. 10(b) is a scanning electron microscope photo at two different magnifications of subject failed area, showing elements of both tensile and fatigue failure modes of the tooth fracture.

A typical fatigue spall for the ausforged gears is shown in Fig. 8(c). The fatigue pit is similar in origin and appearance to the standard forged gear shown in Fig. 8(b).

A fractured tooth and a cross section of the ausforged gears is shown in Fig. 9(c). The fracture was initiated in an area of the tooth which had previously sustained a surface fatigue spall. The cyclic fatigue propagation of the fracture can be clearly seen by the fatigue striations evident in the enlarged section of the fracture cross section [Fig. 10(c)]. Since the tooth endured several load cycles after the start of the tooth fracture, it indicates the basic fracture toughness of the ausforged material and confirms previous work [23, 24] performed on the relative mechanical properties of thermo-mechanically processed steels.

An important observation relevant to the above discussion is illustrated in the grain flow pattern of the standard forged and ausforged gears as shown in Fig. 4(a) and 4(b). The standard forged tooth is very near the final net shape and dimension, while the ausforged tooth still requires considerable machining to achieve the final tooth form, thereby resulting in the elimination of a major portion of the preferential and beneficial grain flow pattern. This would tend to make the ausforged gear tooth less resistant to bending fractures.

SUMMARY OF RESULTS

Four groups of 8.89-centimeter (3.5-in.) pitch diameter spur gears with standard 20° involute profile with tip relief were endurance tested at 350 K (170° F) with a maximum Hertz stress of 17.1×10^{8} newtons per square meter (248,000 psi) and a speed of 10,000 rpm. Three groups were made of VIM-VAR AISI M-50 steel and were either standard machined, standard forged or ausforged. One group was made of case carburized and hardened (VAR) AISI 9310. The lubricant was a super-refined naphthenic mineral oil with an additive package. Test results of the three types of AISI M-50 gears were compared with each other and with the results of the AISI 9310 gears. All tests were run under identical conditions.

The following results were obtained.

1. The pitting fatigue life of the standard forged and ausforged gears was approximately five times that of the VAR AISI 9310 gear and ten times that of the bending fatigue life of the standard machined VIM-VAR AISI M-50 gears run under identical conditions.

2. There is a slight decrease in the 10-percent life of the ausforged gears from that for the standard forged gears. However, the difference in life is not statistically significant.

3. The standard machined AISI M-50 gears failed primarily by gear tooth fracture, while the other AISI M-50 and AISI 9310 gears failed primarily by surface fatigue.

4. The ausforged gears had a slightly greater tendency to fail by tooth fracture than the standard forged gears. This is most likely the result of the better forging grain flow obtained with the standard forged gears.

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TABLE 1. - PROPERTIES OF SUPER-REFINED, NAPHTHENIC, MINERAL-OIL TEST LUBRICANT

Kinematic viscosity, cm^2/sec (cS), at	
266 K (20° F)	2812×10^{-2} ([illegible]2)
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 2. - 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 3. - CHEMICAL COMPOSITION OF GEAR MATERIAL BY PERCENT WEIGHT

Element	AISI M-50 steel VIM-VAR	AISI 9310 VAR
Carbon	0.80	0.10
Manganese	.24	.63
Phosphorous	.006	.005
Sulfur	.005	.005
Silicon	.22	.27
Copper	.06	.13
Chromium	3.98	1.21
Molybdenum	4.18	.12
Vanadium	.98	----
Nickel	.07	3.22
Cobalt	.05	----
Tungsten	.04	----
Iron	Balance	Balance

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TABLE 4. - HEAT TREATMENT PROCESS FOR VIM-VAR AISI CVM M-50

STEEL STANDARD FORGED AND MACHINED

Step	Process	Temperature, K (°F)	Time, hr
1	Preheat (salt bath)	1090 (1500)	0.5
2	Austenitize (salt bath)	1387 (2035)	.1
3	Quench (salt bath)	847 (1065)	.2
4	Air cool to	294 (70)	---
5	Temper	825 (1025)	2
6	Air cool	----	---
7	Sub zero cool	200 (-100)	2
8	Warm to	294 (70)	---
9	Temper	825 (1025)	2

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TABLE 5. - HEAT TREATMENT PROCESS FOR VACUUM ARC REMELTED (VAR) AISI 9310

Step	Process	Temperature, K (°F)	Time, hr
1	Carburize	1172 (1650)	8
2	Air cool to room temperature		
3	Copper plate all over		
4	Reheat	922 (1200)	2.5
5	Air cool to room temperature		
6	Austenitize	1117 (1550)	2.5
7	Oil quench		
8	Sub zero cool	189 (-120)	3.5
9	Double temp	450 (350)	2 each
10	Finish grind		
11	Stress relieve	450 (350)	2

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TABLE 6. - 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 7. - FORGING PROCESS FOR AISI VIM-VAR M-50

Standard forged				Ausforged			
Step	Process	Temperature, K (°F)	Time, hr	Step	Process	Temperature, K (°F)	Time, hr
1	Preheat	1090 (1500)	0.5	1	Preheat	1090 (1500)	0.5
2	Hold	1395 (2050)	.5	2	Austenitize	1409 (2075)	.5
3	Forge			3	Rapid air cool to	1090 (1500	
4	Air cool to	294 (70)		4	Stabilize	1100 (1525)	.1
5	Anneal	1090 (1500)	4	5	Ausforge		
6	Slow furnace cool to	811 (1000)		6	Oil quench to	339 (150)	
7	Air cool to	294 (70)		7	Air cool to	294 (70)	
				8	Stress relief	783 (950)	2

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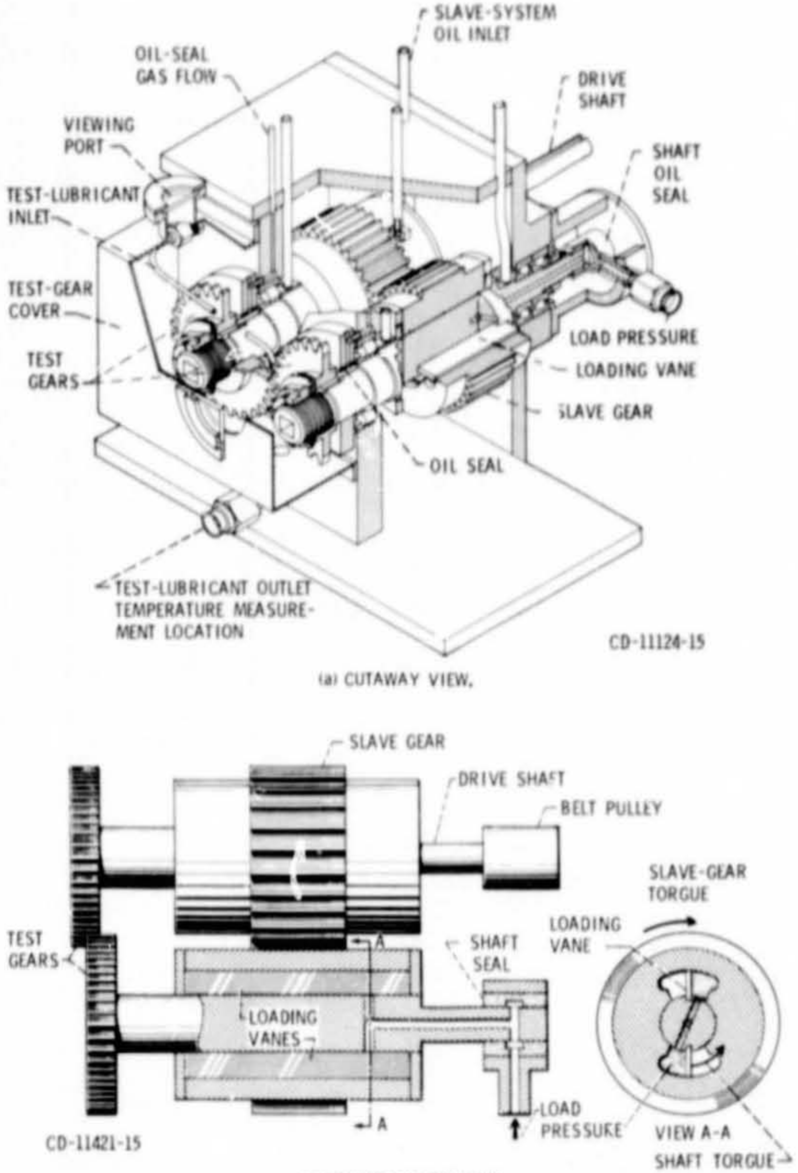

(a) CUTAWAY VIEW.

(b) SCHEMATIC DIAGRAM.

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

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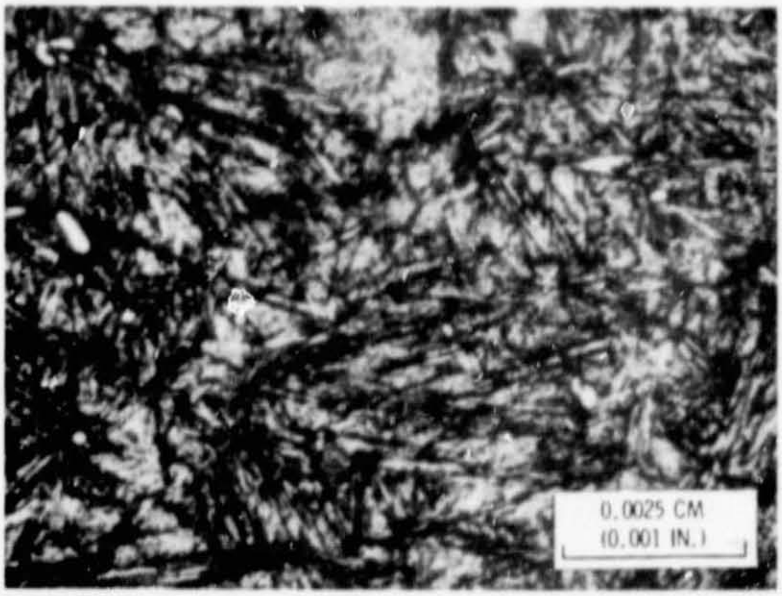
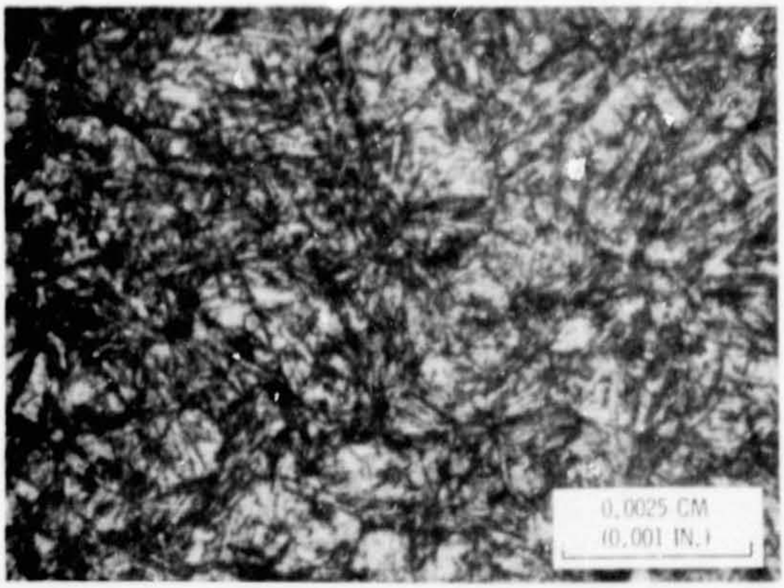
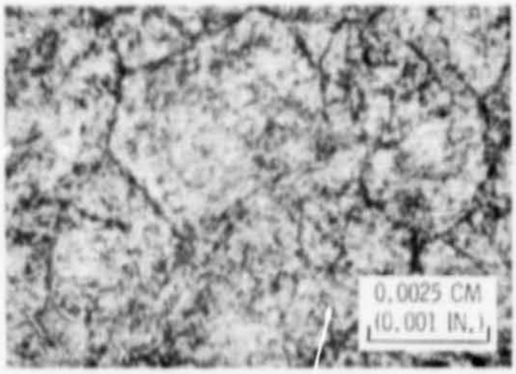


(a) STANDARD MACHINED AISI M-50.

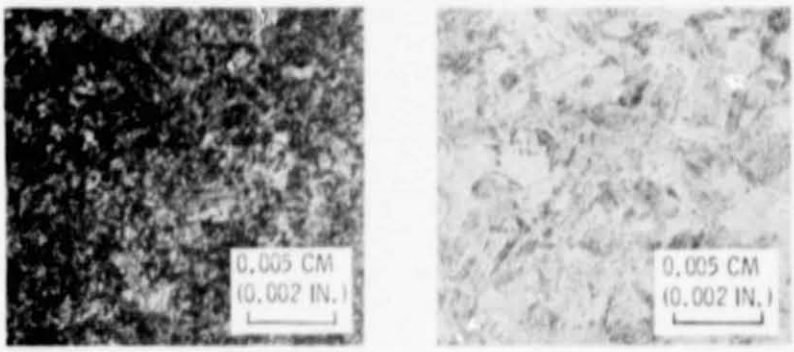


(b) STANDARD FORGED AISI M-50.

Figure 2. - Photomicrograph of standard machined, standard forged and ausforged VIM-VAR M-50 and VAR AISI 9310.



(c) AUSFORGED AISI M-50.



CASE

CORE

(d) VAR AISI 9310.

Figure 2. - Concluded.

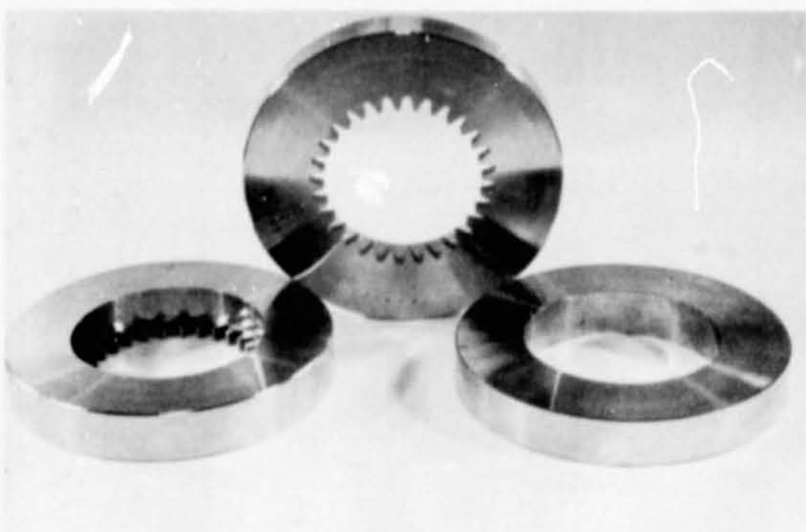


Figure 3. - Tooling inserts utilized for forging gear blanks with and without teeth.

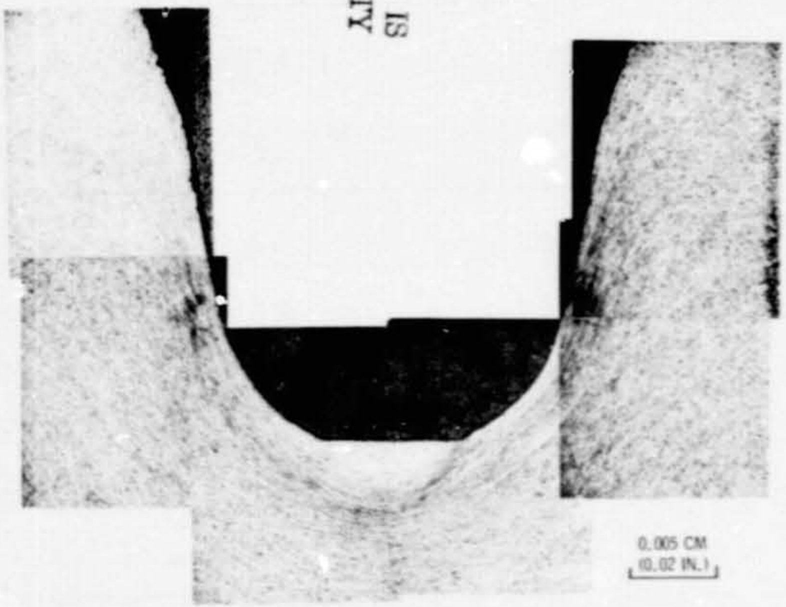


Figure 4(a). - Photomicrograph of macro grain flow pattern in standard forged gear: Etchant, 3 percent nital.

Figure 4(b). - Photomicrograph of macro grain flow pattern in ausforged gear. Etchant, 3 percent nital.

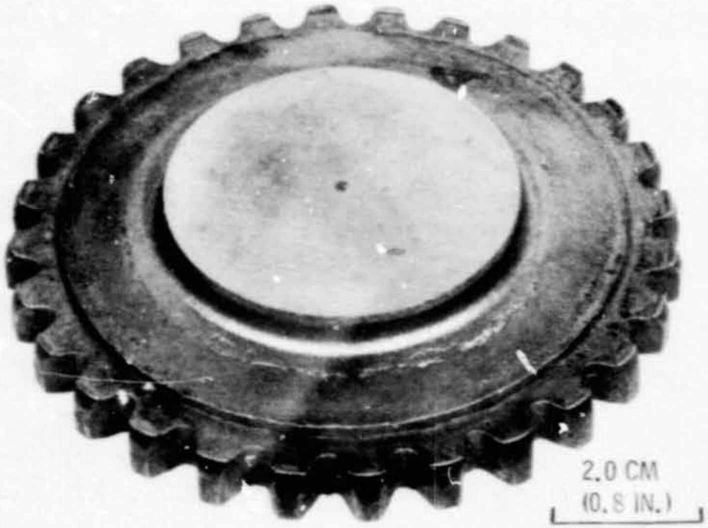


Figure 5(a). - Ausforged gear after initial tooling and process modifications. Tooth fill is approximately 60 percent.

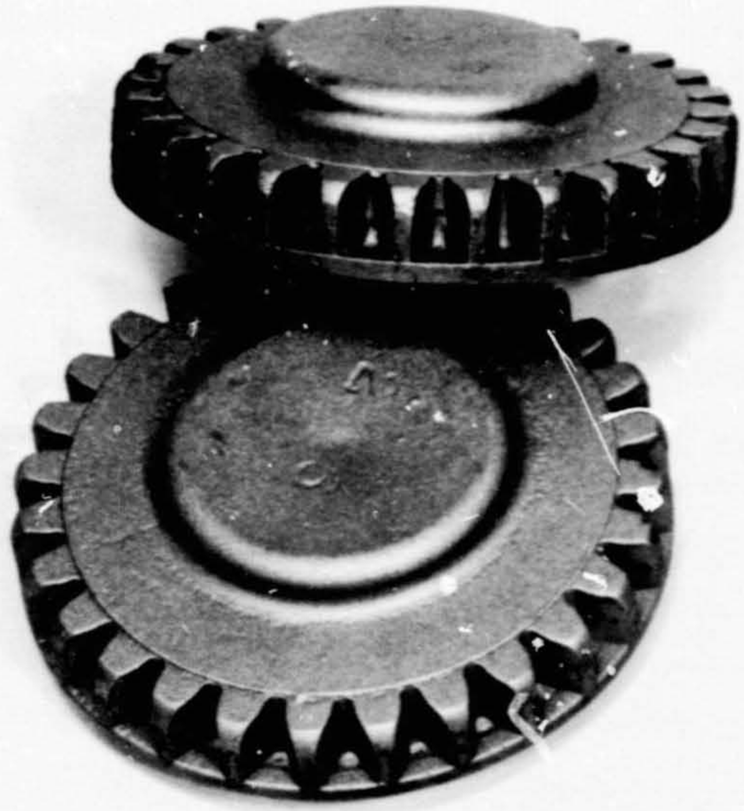
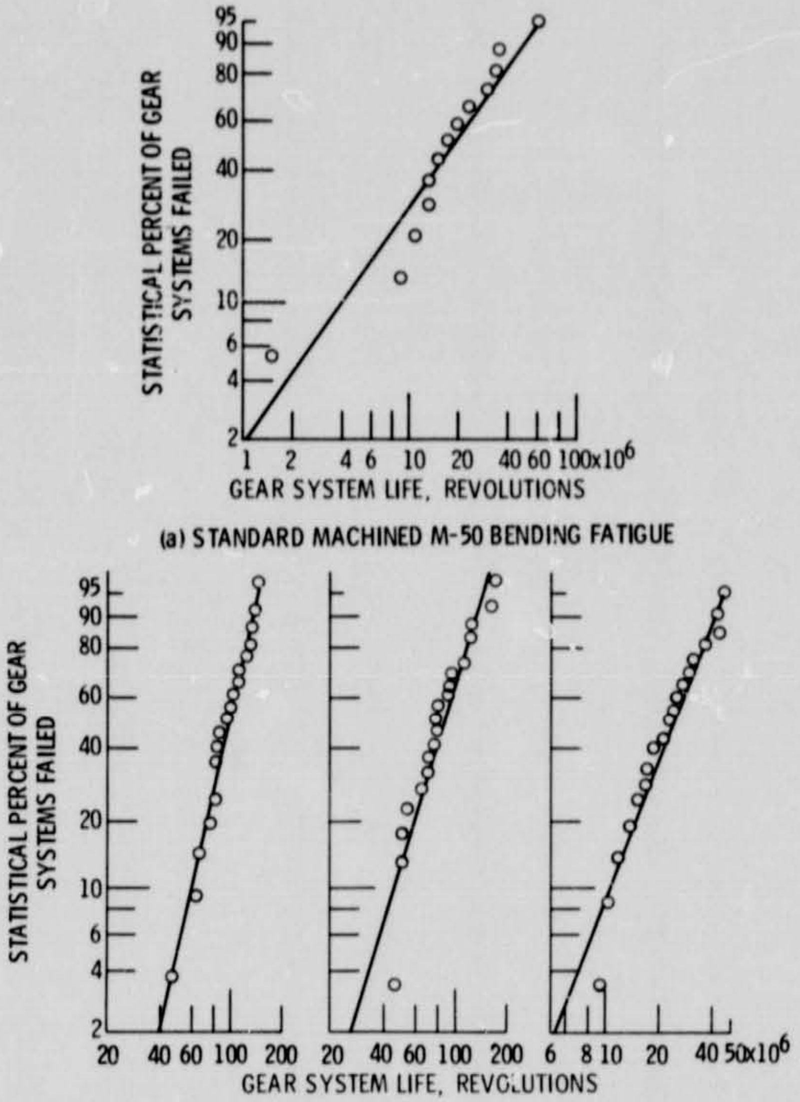


Figure 5(b). - Ausforged gear after final tooling and process modifications.

Figure 6. - Section of die insert after production ausforging run.



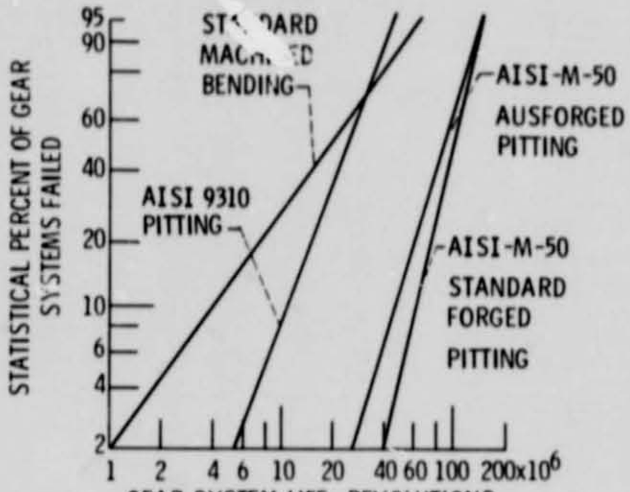
(a) STANDARD MACHINED M-50 BENDING FATIGUE

(b) STANDARD FORGED M-50 PITTING FATIGUE.

(c) AUSFORGED M-50 PITTING FATIGUE.

(d) AISI 9310 PITTING FATIGUE.

Figure 7. - Fatigue lives of spur gear systems made of VIM-VAR AISI M-50 and VAR AISI 9310. Maximum Hertz stress, 17.1×10^8 newtons per square meter (248 000 psi); maximum bending stress at tooth root, 2.67×10^8 newtons per square meter (38 700 psi); speed, 10 000 rpm; temperature, 350 K (170^0 F); lubricant, super-refined naphthenic mineral oil.



(e) SUMMARY OF GEAR LIFE

Figure 7. - Concluded.

(a) STANDARD MACHINED. (b) STANDARD FORGED. (c) AUSFORGED.

Figure 8. - Typical fatigue spall of VIM-VAR AISI M-50 gear teeth. Maximum Hertz stress, 17.1×10^{8} newtons per square meter (248 000 psi); maximum bending stress at tooth root, 2.67×10^{8} newtons per square meter (38 700 psi); speed, 10 000 rpm; temperature, 350 K (170° F); lubricant, super-refined naphthenic mineral oil.

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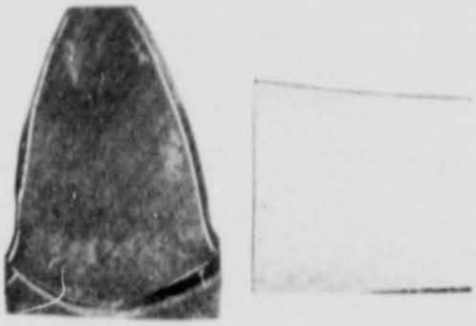
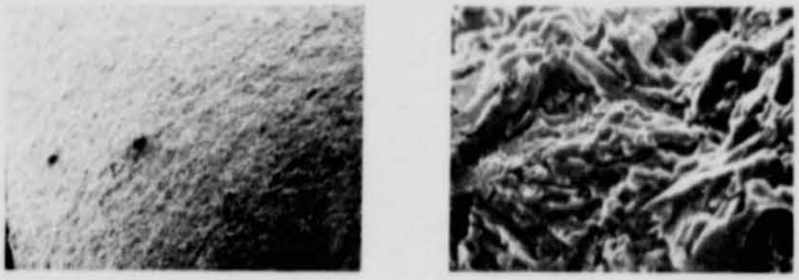


(a) STANDARD MACHINED.

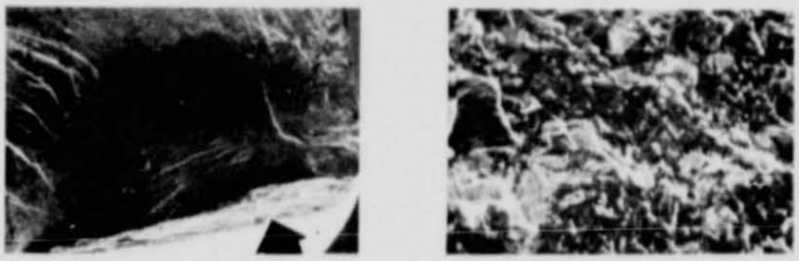
(b) STANDARD FORGED.

(c) AUSFORGED.

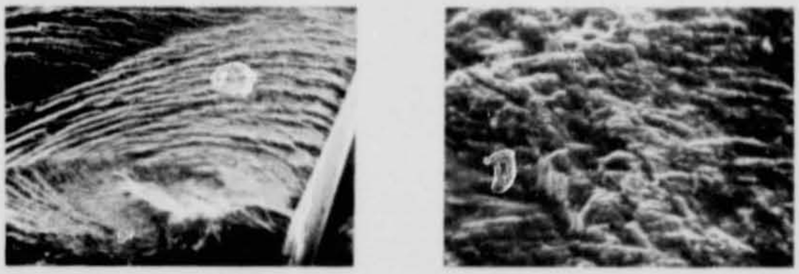
Figure 9. - Cross section of tooth fracture of VIM-VAR AISI M-50 gear teeth. Maximum Hertz stress, 17.1×10^8 newtons per square meter (248 000 psi); maximum bending stress at tooth root, 2.67×10^8 newtons per square meter (38 700 psi); speed, 10 000 rpm; temperature, 350 K (170° F); lubricant, super-refined naphthenic mineral oil.



0.1 CM (0.04 IN.) (a) STANDARD MACHINED. 0.0018 CM (0.0007 IN.)



0.1 CM (0.04 IN.) (b) STANDARD FORGED. 0.002 CM (0.0008 IN.)



0.1 CM (0.04 IN.) (c) AUSFORGED. 0.002 CM (0.0008 IN.)

Figure 10. - Scanning electron photomicrograph of fracture surface of the VIM-VAR AISI M-50 gear tooth at different magnifications.