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COMPARISON OF PITTING FATIGUE LIFE OF AUSFORGED AND STANDARD FORGED AISI M-50 AND AISI 9310 SPUR GEARS

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16. Abstract

Standard forged and ausforged spur gears made of vacuum-induction-melted, consumable-electrode, vacuum-arc-remelted (VIM-VAR) AISI M-50 steel were tested under conditions that produced fatigue pitting. The gears were 8.89 cm (3.5 in.) in pitch diameter and had tip relief. The M-50 standard forged and ausforged test results were compared with each other. They were then compared with results for machined vacuum-arc-remelted (VAR) AISI 9310 gears tested under identical conditions. Both types of M-50 gears had lives approximately five times that of the 9310 gears. The life at which 10 percent of the M-50 ausforged gears failed was slightly less than that at which the M-50 standard forged gears failed. The ausforged gears had a slightly greater tendency to fail by tooth fracture than did the standard forged gears, most likely because of the better forging and grain flow pattern of standard forged gears.

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COMPARISON OF PITTING FATIGUE LIFE OF AUSFORGED AND STANDARD FORGED AISI M-50 AND AISI 9310 SPUR GEARS

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SUMMARY

Standard forged and ausforged spur gears made of vacuum-induction-melted, consumable-electrode, vacuum-arc-remelted (VIM-VAR) AISI M-50 steel were tested under conditions that produced fatigue pitting. The gears were 8.89 cm (3.5 in.) in pitch diameter and had a standard 20° involute profile with tip relief. All gears were tested at a speed of 10 000 rpm, a maximum pitch-line Hertz stress of 17.1×10^{8} N/m^{2} (248 000 psi), and a temperature of 350 K (170° F) and were lubricated with a super-refined naphthenic mineral oil having an additive package.

Test results for the M-50 standard forged gears were compared with those for the M-50 ausforged gears. Both types of M-50 gears were then compared with machined, vacuum-arc-remelted (VAR) AISI 9310 gears tested under identical conditions.

The standard forged and ausforged M-50 gears had lives approximately five times that of the 9310 gears. The life at which 10 percent of the M-50 ausforged gears failed was slightly less than that at which the standard forged M-50 gears failed. However, the difference in life is not statistically significant.

The ausforged gears had a slightly greater tendency to fail by tooth fracture than the standard forged gears, probably because of the better forging and grain flow obtained with the standard forged gears.

INTRODUCTION

Advanced aircraft engine gearboxes and helicopter transmissions require weight redution, increased service life, and greater reliability. The gearing in these applications is expected to carry higher loads at higher temperatures and still provide in-

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creased life, low maintenance, and high reliability. These requirements place stringent demands on the gear materials.

Before improvements can be made in gear material technology, the failure characteristics and mechanical properties must be defined for existing and potential gear materials. As a result, two approaches to gear material technology can be pursued. The first consists primarily of life testing and failure analysis. The second is aimed at improving material properties.

A fabrication method which has the potential to improve the strength and life of gear teeth is termed "ausforging." Ausforging is a thermomechanical process which comprises high-energy-rate forging of steels while the material is in the meta-stable austenitic condition (ref. 1). A number of researchers have investigated this process (refs. 2 to 5). The application of ausforging to machine elements such as rolling-element bearings was first reported in reference 6.

The results of reference 6 showed that the rolling-element (pitting) fatigue life of ausforged AISI M-50 which was 80-percent plastically deformed (as measured by reduction in cross-sectional area) was eight times greater than the life obtained with conventionally processed AISI M-50 material. Similar results were obtained with 35-mm-bore, single-row radial ball bearings (ref. 7), as shown in figure 1. Some of the ausformed balls produced for these bearings were independently evaluated (ref. 8). These results also indicate a significant improvement in fatigue life over that of conventional AISI M-50 material. Additional work was performed on larger diameter bearings (ref. 9). This work also demonstrated the potential life improvements with the ausforging process.

AISI M-50 material for use in the manufacture of spur gears was also investigated (refs. 10 to 12). The results of this investigation indicated that the AISI M-50 material had the potential for long-life gear application. However, because the material was through-hardened, there was a tendency for a gear tooth to fracture from bending fatigue after extended running subsequent to suffering pitting fatigue failure. The surface spall acted as a stress raiser, aggravating the bending fatigue. Another problem occurred with AISI M-50 gears manufactured with tip relief. That is, they failed primarily by bending fatigue as opposed to surface pitting (refs. 11 and 12) and thus were relatively short lived. Ausforging of AISI M-50 was expected to significantly reduce the bending fatigue problem because of the increased resistance of ausforged steel to crack initiation or propagation and its improved fracture-toughness characteristic. It is speculated in references 13 and 14 that this resistance to crack propagation is one of the main factors contributing to the high fatigue strength of ausforged steels. The application of ausforging to gears was therefore a logical progression in the utilization of thermomechanical processing techniques to improve reliability. The standard forged and ausforged gears were developed under NASA contract (ref. 15).

The objectives of the research reported herein were to compare, under closely controlled test conditions, the fatigue lives and failure modes of spur gears made of standard forged and ausforged AISI M-50 steel and to compare these lives with those of machined AISI 9310 gears.

In order to accomplish these objectives, tests were conducted with 8.89-cm- (3.5-in.-) pitch-diameter spur gears made of forged and ausforged vacuum-induction-melted (VIM), consumable-electrode, vacuum-remelted (VAR) AISI M-50 steel. The test conditions were a temperature of 350 K (170° F), a maximum contact (Hertz) stress of 17.1×10^8 N/m^2 (248 000 psi), and a speed of 10 000 rpm. All experimental results were obtained with a superrefined naphthenic mineral oil having a proprietary additive package (from one lubricant batch) plus a 5-percent antiwear additive. All gears were manufactured from a single lot of VIM-VAR AISI M-50 steel.

This investigation was conducted in the U.S. customary system of units. Conversion to the International System of Units (SI) was for reporting purposes only.

APPARATUS, SPECIMENS, AND PROCEDURE

Gear Test Apparatus

The gear fatigue tests were performed in the NASA Lewis Research Center's gear-fatigue test machine (fig. 2). This gear testing machine 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 gear testing machine is shown in figure 2(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 lubrication systems are separated at the gearbox shafts by pressurized labyrinth seals, with nitrogen as the seal gas. The test-gear lubricant is filtered through a 5-micron nominal fiberglass filter. The test lubricant can be heated electrically with an immersion heater. The skin temperature of the heater is closely controlled to prevent a "hot spot" condition that would overheat the test lubricant.

A vibration transducer mounted on the gearbox is used to automatically shut off the gear testing machine when a gear-surface fatigue failure 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 gear testing machine 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 superrefined naphthenic mineral oil with 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 cm^3/min, 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°±10° F), and the lubricant outlet temperature was nearly constant at 350±3 K (170°±5° 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. 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 (ref. 16).

Test Gears

The test gears were manufactured from a single lot of vacuum-induction-melted (VIM), consumable-electrode, vacuum-arc-remelted (VAR) AISI M-50 steel. The chemical composition of this material is given in table III. This tool steel is currently used in the manufacture of main-shaft engine bearings for jet engines. It has also been used in limited application for gears in aircraft accessory gearboxes. This material has shown good load-carrying capacity in rolling-element bearings at temperatures to 589 K (600° F) (ref. 17).

Test-gear dimensions are given in table IV. All gears have a nominal surface finish on the tooth face of 0.406 μm (16 μin.) rms and a standard 20° involute tooth profile with tip relief. Tip relief was 0.0010 to 0.0015 cm (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.

Standard forged gears. - A controlled-energy-flow forming technique (CEFF) was used during the normal forging of the gears (ref. 15). This high-velocity metalworking procedure has been a production process for several years (ref. 18). A number of iterations were required before the optimum forging sequence was established. The optimum forging sequence for the standard forged gear is shown in table V.

The initial two forging trials resulted in a considerable lack of fill at the outer gear-tooth periphery. This condition was remedied by increasing the volume of the forging preforms and increasing the forging temperature from 1366 to 1394 K (2000° to 2050° F). Comparative measurements of parts sectioned after the fourth trial showed the parts to be nearly perfect except that they did not have the 0.25 to 0.38 mm (0.010 to 0.015 in.) of excess metal required for final machining. After a final modification, dimensionally acceptable gear forgings were produced. The die inserts for ausforged and standard forged gears are shown in figure 3.

Gear samples were cross sectioned and etched to study the grain flow pattern. Figure 4(a) is representative of the grain flow pattern for the standard forged gear. Figure 5(a) is a photomicrograph of the standard forged gear structure. The hardness of the gears was 62 to 64 Rockwell C. The hardening cycle for the standard forged gears is given in table VI. Metallographic examination revealed no evidence of decarburization. X-ray diffraction measurements showed the retained austenite level to be less than one percent.

Ausforged gears. - The initial ausforging trial was performed on a Model HE-10 CEFF machine, which has a maximum energy output of 102 000 N-m (75 000 ft-lbf). This machine had been adequate for the production of the standard forged gear. At the lower (1075 K (1475° F)) ausforming temperature, however, the HE-10 CEFF machine did not have sufficient capacity, as illustrated by the forging shown in figure 6(a). This photograph clearly demonstrates the minimal movement of the M-50 material into the gear-tooth configuration of the die. It was therefore decided to adapt the tooling to a Model HE-55 CEFF machine, which has a capacity of 542 000 N-m (400 000 ft-lbf). The first forging trial with the higher energy machine was not satisfactory (fig. 6(b)). Investigation revealed that die closure had taken place, causing the ejector to deflect in an elastic manner. This deflection also resulted in the generation of teeth mislocated from the central hub, as indicated in figure 6(b). As a result of the significant ejector deflection, much of the forging energy was absorbed into the dies and therefore the efficiency of energy transfer to the workpiece was poor.

An additional tooling and procedural modification remedied this problem to some extent and produced the gear shown in figure 6(c). The teeth, however, were still only approximately 60 percent formed. Tooth fill was improved by a further change in the die configuration. This change consisted of adopting a minimal scallop configuration, intended primarily to permit a larger radius at the top of the die tooth form (gear-tooth radius). This larger radius would alleviate the apparent restrictive metal flow. In addition, the ausforging temperature was increased to 1103 K (1525° F) in order to achieve improved flow characteristics. The subsequent forging trial produced the parts shown in figure 6(d). A full tooth configuration was essentially achieved, although the lack of fill of the upper part of the teeth still made this a marginal part in terms of the final machined tooth width of 0.64 cm (0.25 in.).

One final modification was made to the die; the height of the tooth insert tooling was increased, coupled with an equivalent increase in the volume of the preform. These measures were designed to increase the tooth height and thus to provide adequate material for final machining. These corrective steps were successful and resulted in the production of dimensionally acceptable parts as illustrated in figure 6(e). The only problem arising from this last modification was a heavier-than-expected flash area, which required more machining time during the final manufacturing steps. The die inserts did not exhibit significant wear after 25 gear forgings, as shown in figure 7. While there is some evidence of scoring and upsetting, no serious damage or tooth breakage was encountered.

The good grain flow pattern obtained in the ausforged gears is shown in figure 4(b). However, this ausforged gear did not have as close a final tooth shape as the standard forged gear. As a result, some of the potential benefits of good grain flow were lost during machining. Figure 5(b) is a photomicrograph of an ausforged gear structure. The hardness of the gear was 62 to 64 Rockwell C. As with standard forged gears, metallographic examination revealed no evidence of decarburization. Retained austenite was less than one percent.

Test Procedure

After the test gears were cleaned to remove the preservative, they were assembled on the gear testing machine. The test gears were run in an offset condition with a 0.31-cm (0.120-in.) tooth-surface overlap to give a load surface on the gear face of 0.28 cm (0.110 in.) of the 0.635-cm- (0.250-in.-) wide gear, allowing for the edge radius of the gear teeth. By testing both faces of the gears, a total of four fatigue tests could be run for each set of gears. All tests were "run in" at a load of 1156 N/cm (661 lb/in.) for 1 hour. The load was then increased to 5788 N/cm (3305 lb/in.) with a 17.1×10^{8}-N/m^2 (248 000-psi) pitch-line Hertz stress. At the pitch-line load the tooth bending stress was 2.48×10^{8} N/m^2 (36 000 psi) if plain bending was assumed. However, because there was an offset load, an additional stress was imposed on the tooth bending stress. Combining the bending and torsional moments gave a maximum stress of 2.67×10^{8} N/m^2 (38 700 psi). The effect of tip relief, which will further increase the bending stress, was not considered.

The test gears were operated at 10 000 rpm, which gave a pitch-line velocity of 46.55 m/sec (9163 ft/min). Lubricant was supplied to the inlet mesh at 800 cm^3/min

319 ± 6 K ($115^{\circ} \pm 10^{\circ}$ F). Each test was run continuously 24 hours a day until failure. The test was shut down automatically by the vibration-detection transducer located on the gearbox, adjacent to the test gears. The lubricant was circulated through a nominal 5-micron fiberglass filter to remove wear particles. A total of 3800 cm^3 (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 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 inlet oil temperature was considerably lower. It is probable that the gear-surface temperature could be even higher than the outlet oil temperature, especially at the endpoints of sliding contact. The EHD film thickness for these conditions was computed to be 0.66 μm (26 μin.), which gave a ratio of film thickness to composite surface roughness h/σ of 1.13.

RESULTS AND DISCUSSION

The AISI M-50 gears with standard forged teeth and with ausformed teeth were tested under a load of 5788 N/cm (3305 lb/in.), which produced a maximum Hertz stress at the pitch line of 17.1×10^{8} N/m^2 (248 000 psi). The gears were manufactured with a 0.0013-cm (0.0005-in.) tip relief and with a crown to reduce edge effects. The lubricant was a superrefined naphthenic mineral oil with an extreme-pressure additive package. The gears failed either by surface fatigue pitting or, in some cases, by tooth fracture. Test results were statistically evaluated by the methods of reference 20. For purposes of evaluation a pair of mating gears was considered as a single test.

The statistical results of the tests with the standard forged gears are shown in figure 8(a). These results, plotted on Weibull coordinates, represent those gears that failed by surface pitting fatigue. Weibull coordinates are the log-log of the reciprocal of the probability of survival graduated as the statistical percentage of specimens failed (ordinate) against the log of time to failure or system life (abscissa). Two of the 19 gear tests included in these data also failed from tooth fracture after a fatigue spall and after the gears had been run for some time beyond the pitting fatigue failure.

A typical fatigue spall for a standard forged gear is shown in figure 9(a). Metallurgical examination indicated that the fatigue spalls were of subsurface origin and initiated at or near the pitch radius in the region of maximum Hertz stress.

A fractured tooth of a standard forged gear is shown in cross section in figure 10(a). Here the tooth fracture originated at the location of a previous surface fatigue spall.

The failure propagated in a cyclic fatigue mode, as shown by the fatigue striations, to a point where it transitioned to a tensile failure resulting in total separation of the gear tooth, as shown in figure 11(a). One other standard forged gear failed by tooth fracture as the result of increased dynamic loads from an adjacent tooth with a surface fatigue spall. This fatigue spall was overrun for several hours, resulting in a considerable area of the tooth surface being removed. The tooth load was then shifted to the adjacent tooth because of increased pitch length.

The statistical results of the tests with the ausforged gears are shown in figure 8(b). These results, plotted on Weibull coordinates, represent those gears that failed by surface pitting fatigue. The 10-percent life of the ausforged gears was slightly less than that of the standard forged gears. However, the difference in life is not statistically significant.

A typical fatigue spall of an ausforged gear is shown in figure 9(b). The fatigue pit is similar in origin and appearance to that of the standard forged gear shown in figure 9(a).

A fractured tooth of an ausforged gear is shown in cross section in figure 10(b). Again the fracture was initiated in an area of the tooth which had previously sustained a surface fatigue spall. Here again the propagation of the fracture indicates its cyclic fatigue nature. The tooth endured several load cycles after the start of tooth fracture. This indicates that the ausforged material has improved fracture toughness and confirms previous work (refs. 13 and 14) performed on the relative mechanical properties of thermomechanically processed steels.

Because of the ausforging process and the previously discussed die modification, some of the preferential grain flow inherent in the ausforged material was removed during the final machining of the ausforged gears. As a result, the ausforged gears did not have as good a grain flow pattern in the critical tooth root area as the standard forged gears. This would tend to make the ausforged gear tooth less resistant to bending fatigue and subsequent fracture. Of the 21 tests completed on the ausforged AISI M-50 gears, five tests resulted in gear-tooth fracture. All these fractures were the result of prior surface fatigue spalls and showed evidence of being fatigue-type fractures.

By way of comparison, figure 8(c) is a summary Weibull plot of the pitting fatigue lives of standard forged and ausforged VIM-VAR AISI M-50 gears along with a plot of identical, machined, case carburized and hardened, VAR AISI 9310 gears (ref. 21) tested under identical conditions. It can be seen that the forged and ausforged AISI M-50 gears had approximately five times the 10-percent life of the AISI 9310 gears. Since the standard forged and ausforged gears had approximately the same endurance life, the added cost and complexity of producing ausforged gears would suggest that the standard forged gear is preferrable.

SUMMARY OF RESULTS

Standard forged and ausforged spur gears made of vacuum-induction-melted, vacuum-arc-remelted (VIM-VAR) AISI M-50 steel were tested under conditions that produced fatigue pitting. The gears were 8.89 cm (3.5 in.) in pitch diameter and had a standard 20° involute profile with tip relief. Test conditions were a temperature of 350 K (170° F), a maximum Hertz stress of 17.1×10^{8} N/m^2 (248 000 psi), and a speed of 10 000 rpm. The lubricant was a superrefined naphthenic mineral oil with an additive package. Test results for the standard forged M-50 gears were compared with results for the ausforged AISI M-50 gears. These results were then compared with previous results for vacuum-arc-remelted (VAR) AISI 9310 gears tested under identical conditions. The following results were obtained:

1. The life of the standard forged and ausforged AISI M-50 gears was approximately five times that of the machined AISI 9310 gears tested under identical conditions.

2. The 10-percent life of the ausforged gears was slightly less than that of the standard forged gears. However, the difference in life is not statistically significant.

3. The ausforged gears had a slightly greater tendency to fail by tooth fracture than the standard forged gears, most likely because of the better forging and grain flow obtained with the standard forged gears.

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National Aeronautics and Space Administration,
Cleveland, Ohio, May 9, 1975,
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TABLE I. - PROPERTIES OF SUPERREFINED NAPHTHENIC

MINERAL OIL USED AS TEST LUBRICANT

Kinematic viscosity, cm^2/sec (cS), at-	
266 K (20^{o} F)	2812×10^{-2} (2812)
311 K (100^{o} F)	73×10^{-2} (73)
372 K (210^{o} F)	7.7×10^{-2} (7.7)
478 K (400^{o} F)	1.6×10^{-2} (1.6)
Flashpoint, K (^{o}F)	489 (420)
Autoignition temperature, K (^{o}F)	664 (735)
Pour point, K (^{o}F)	236 (-35)
Density at 289 K (60^{o} F), g/cm^3	0.8899
Vapor pressure at 311 K (100^{o} F), mm Hg (or torr)	0.01
Thermal conductivity at 311 K (100^{o} F), J/(m)(sec)(K) (Btu/(hr)(ft)(^{o}F))	0.04 (0.0725)
Specific heat at 311 K (100^{o} F), J/(kg)(K) (Btu/(lb)(^{o}F))	581 (0.450)

TABLE II. - PROPERTIES OF LUBRICANT ADDITIVE ANGLAMOL 81

Phosphorous content, percent by weight	0.66
Sulfur content, percent by weight	13.41
Specific gravity	0.982
Kinematic viscosity at 372 K (210^{o} F), cm^2/sec (cS)	29.5×10^{-2} (29.5)

TABLE III. - CHEMICAL COMPOSITION

OF TEST MATERIALS

Element	AISI M-50	AISI 9310
	Content, wt %	
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

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. - OPTIMUM FORGING PROCESS FOR VACUUM-INDUCTION-MELTED,

CONSUMABLE-ELECTRODE, VACUUM-ARC-REMELTED (VIM-VAR)

AISI M-50 STEEL GEARS

(a) Standard forged

Step	Process	Temperature		Time, hr
		K	^{o}F	
1	Preheat	1088	1500	0.5
2	Austenitize	1394	2050	.5
3	Forge	----	----	---
4	Air cool to	294	70	---
5	Anneal	1088	1500	4
6	Slow furnace cool to	811	1000	---
7	Air cool to	294	70	---

(b) Ausforged

Step	Process	Temperature		Time, hr
		K	^{o}F	
1	Preheat	1088	1500	0.5
2	Austenitize	1408	2075	.5
3	Rapid air cool to	1088	1500	---
4	Stabilize	1103	1525	.1
5	Ausforge	----	----	---
6	Oil quench to	339	150	---
7	Air cool to	294	70	---
8	Stress relief	783	950	2

TABLE VI. - HEAT TREATMENT PROCESS FOR VACUUM-INDUCTION-MELTED, CONSUMABLE-ELECTRODE, VACUUM-ARC-REMELTED (VIM-VAR) AISI M-50 STANDARD FORGED STEEL GEARS

Step	Process	Temperature		Time, hr
		K	°F	
1	Preheat (salt bath)	1088	1500	0.5
2	Austenitize (salt bath)	1386	2035	.1
3	Quench (salt bath)	847	1065	.2
4	Air cool to	294	70	---
5	Temper	825	1025	2
6	Air cool	----	----	---
7	Subzero cool	200	-100	2
8	Warm to	294	70	---
9	Temper	825	1025	2

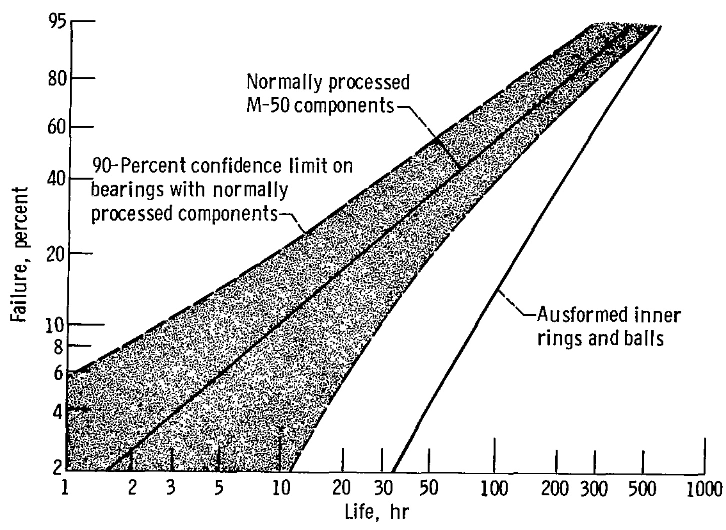
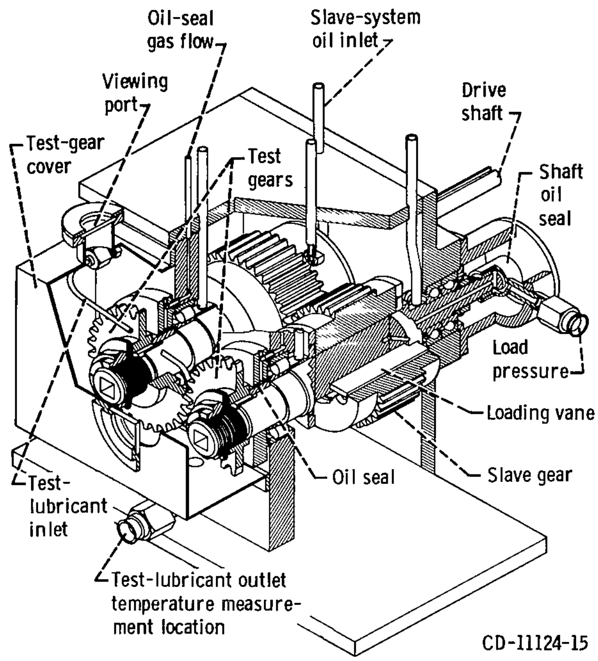
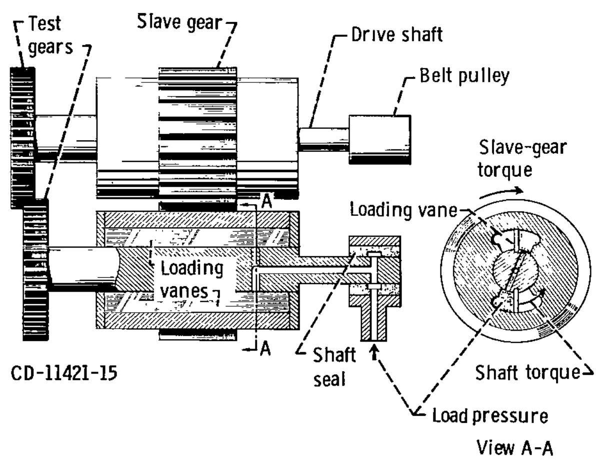


Figure 1. - Effect of ausforming on fatigue life of 35-millimeter-bore, vacuum-induction-melted, consumable-electrode, vacuum-arc-remelted (VIM-VAR) AISI M-50 radial ball bearings. (From ref. 7.)



(a) Cutaway view.



(b) Schematic diagram.

Figure 2. - NASA Lewis Research Center's gear-fatigue test machine.

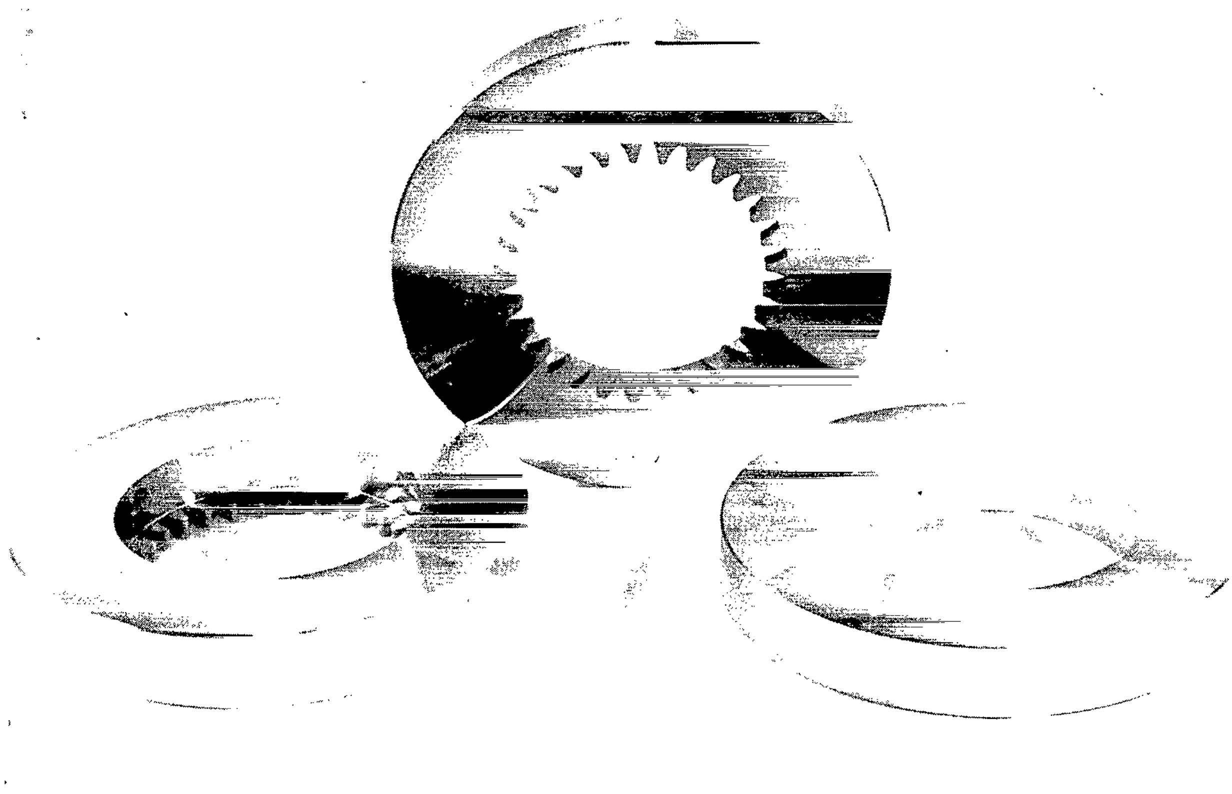
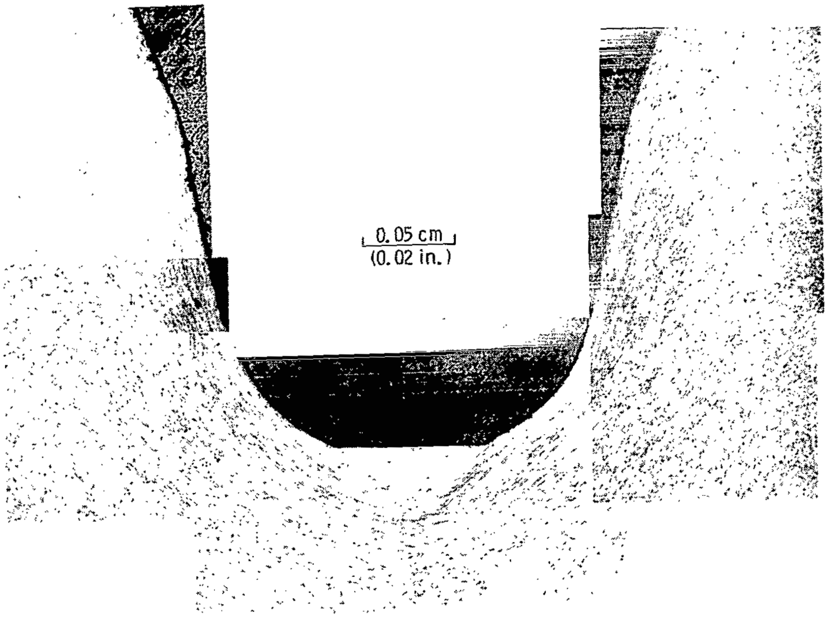
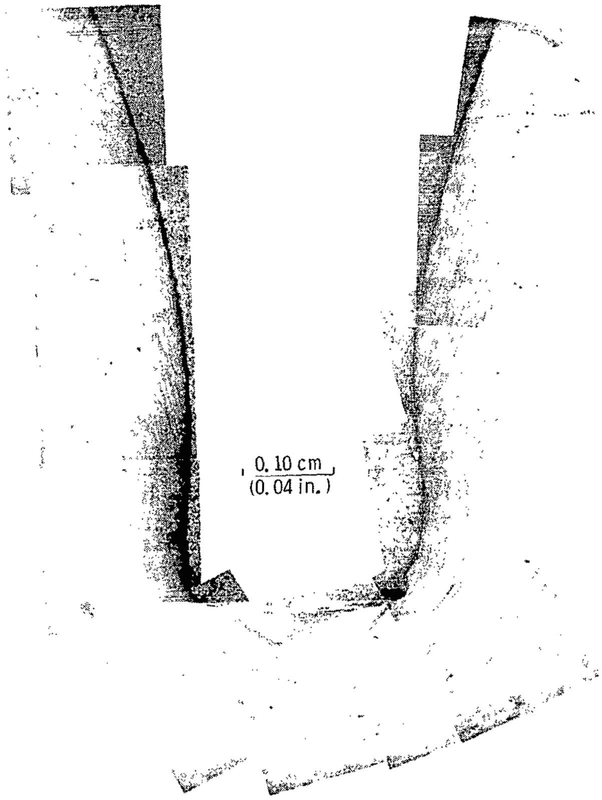


Figure 3. - Tooling inserts used for forging gear blanks with and without teeth.

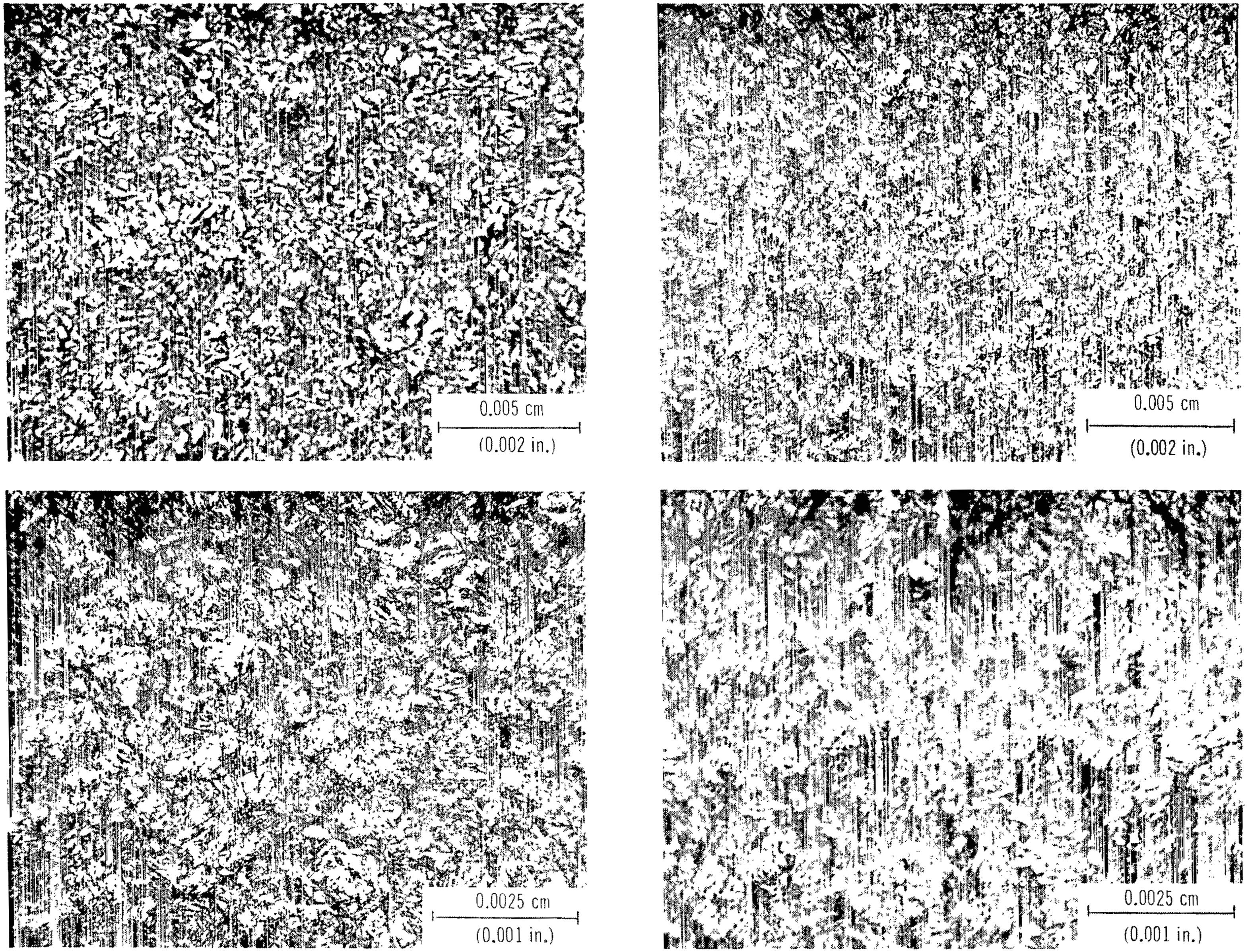


(a) Standard forged gear.



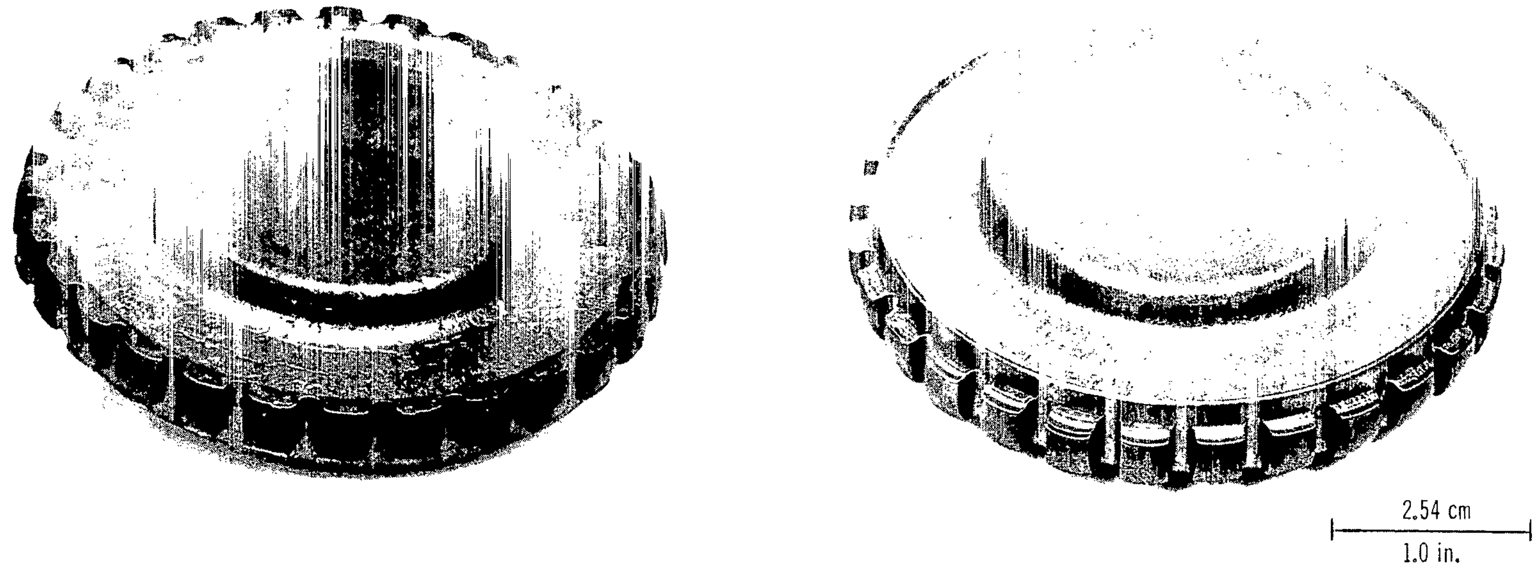
(b) Ausforged gear.

Figure 4. - Photomicrographs of macro-grain-flow pattern in forged AISI M-50 gears. Etchant, 3 percent Nital.



(a) Standard forged gear. (b) Ausforged gear.

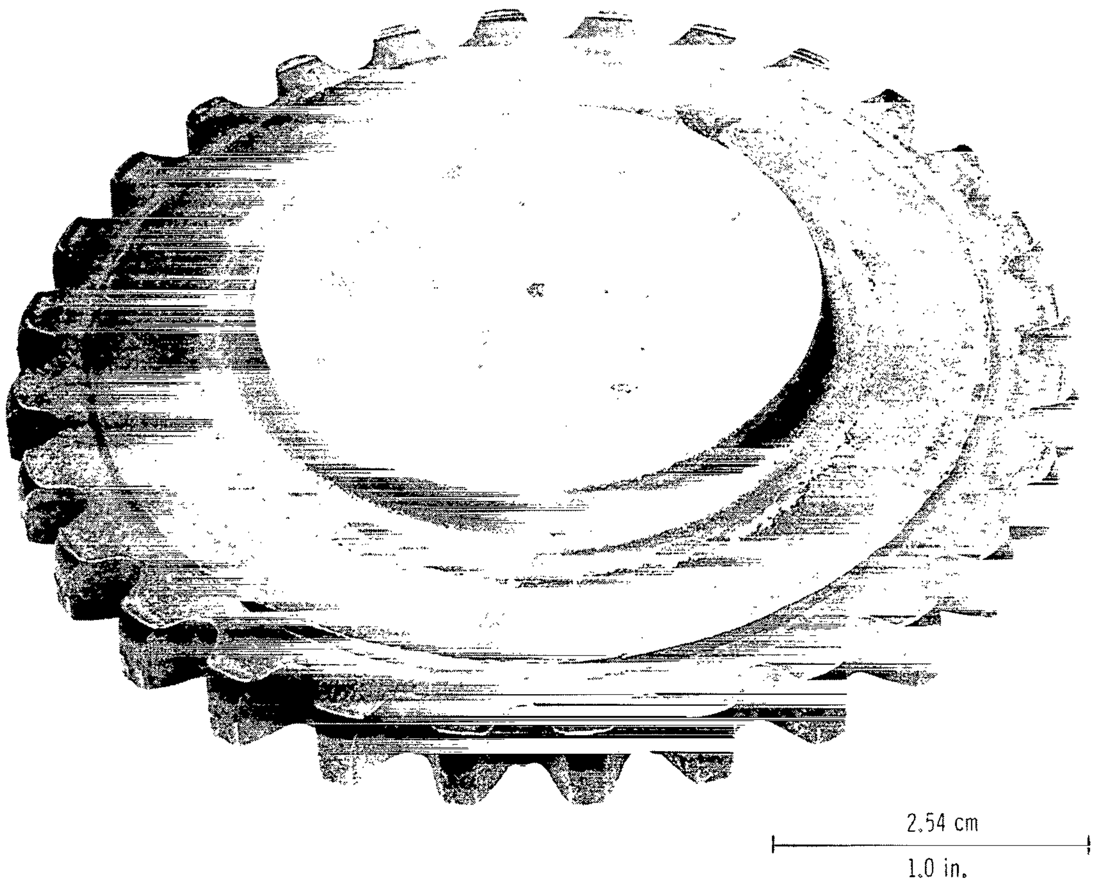
Figure 5. - Typical microstructures in teeth of standard forged and ausforged VIM-VAR AISI-M50 gears. Etchant, 3 percent Nital.



(a) Initial blank made on Model HE-10 controlled-energy-flow-forming (CEFF) machine. (Minimal amount of metal movement into tooth configuration.)

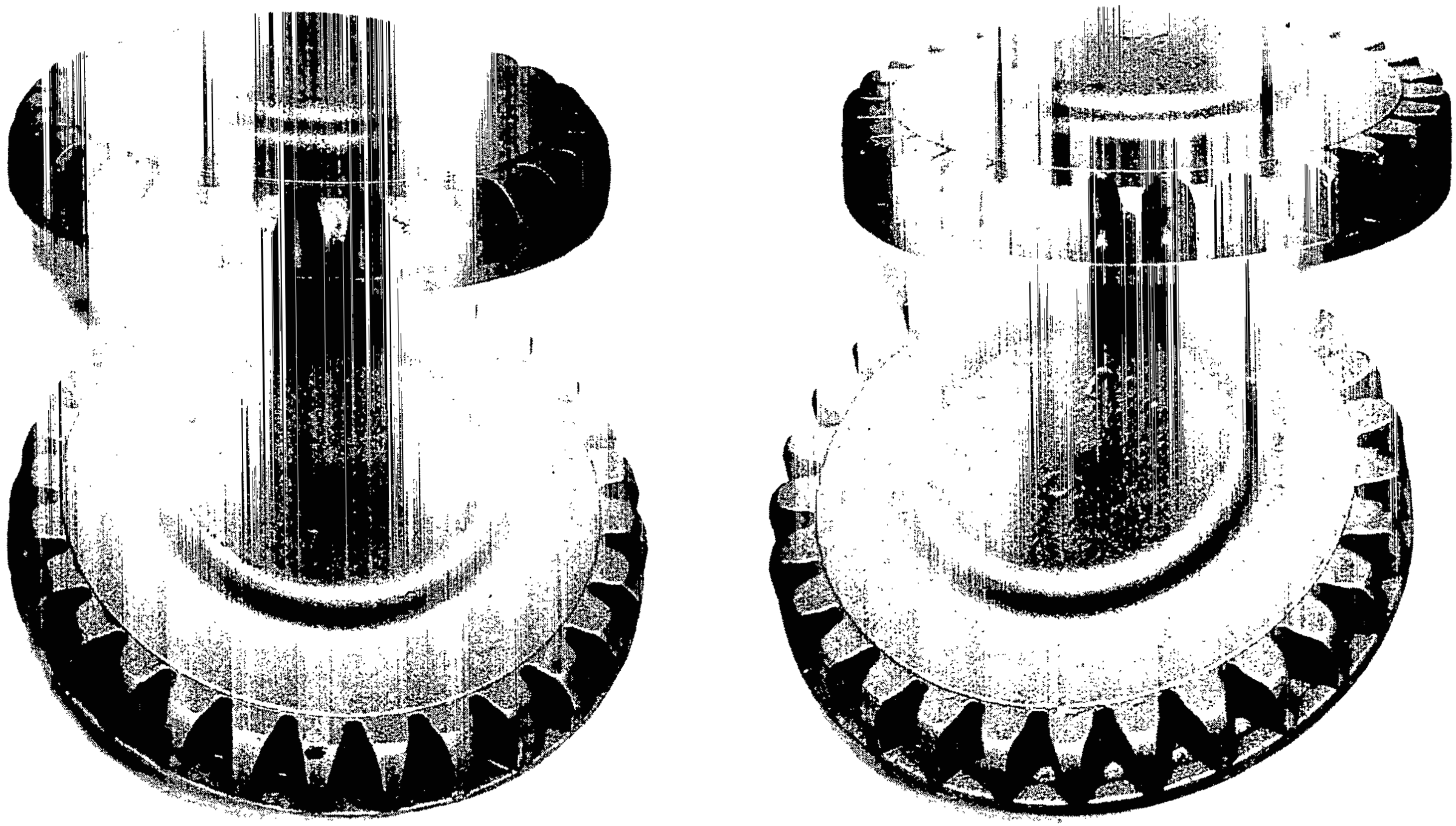
(b) First ausforged gear forging made on Model HE-55 CEFF machine. (Tooth fill better than that in fig. 6(a) but still unsatisfactory.)

Figure 6. - Ausforged gear blanks during various stages of forging.



(c) Gear after initial tooling and procedural modification made on Model HE-55 CEFF machine. (Tooth fill approximately 60 percent.)

Figure 6. - Continued.



(d) Gear forgings after additional tooling and die modifications made on Model HE-55 CEFF machine. (100-Percent tooth configuration has been established although lack of fill at bottom (upper surfaces in photograph) has created condition of minimal tooth width.)

(e) Gear forgings after increasing height of tooling made on Model HE-55 CEFF machine.

Figure 6. - Concluded.

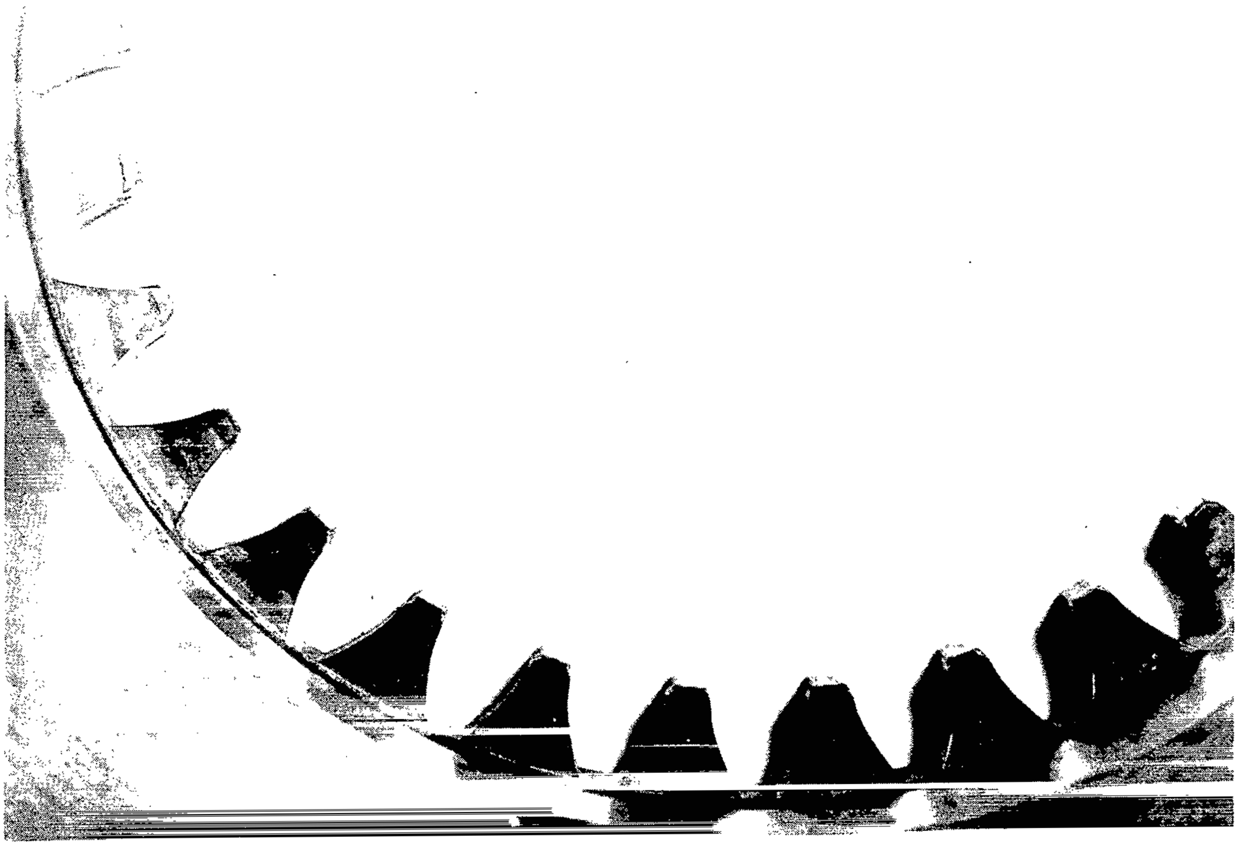
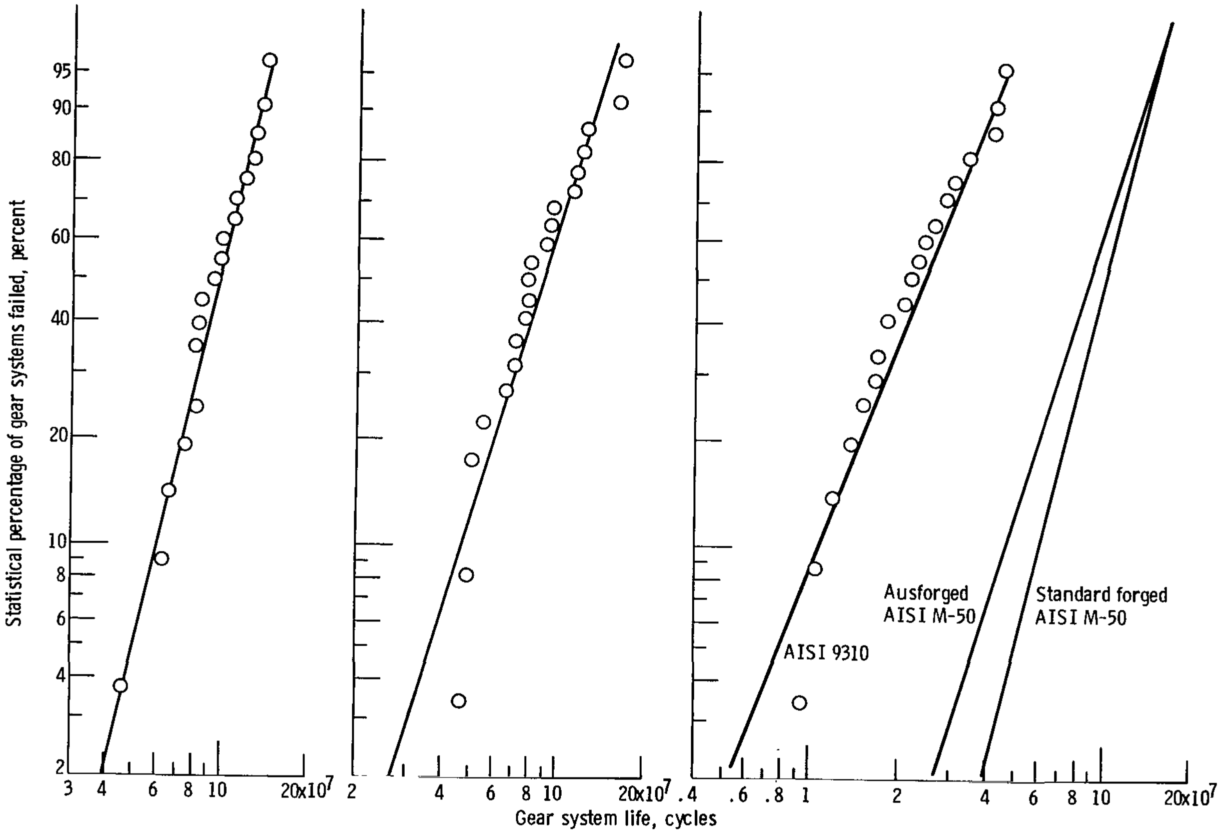


Figure 7. - Section of die insert after production ausforging run.

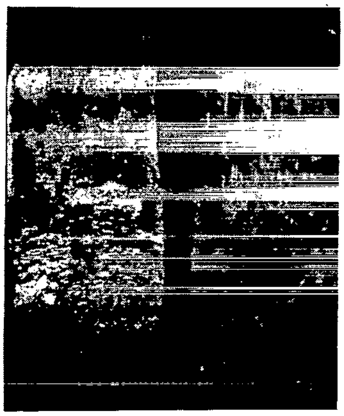


(a) Standard forged AISI M-50 gears.

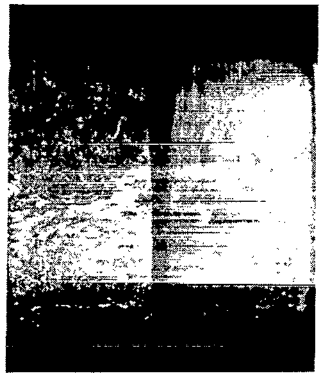
(b) Ausforged AISI M-50 gears.

(c) AISI 9310 gears compared with standard forged and ausforged AISI M-50 gears.

Figure 8. - Pitting fatigue lives of spur gear systems made of standard forged and ausforged AISI M-50 and AISI 9310 steel. Maximum Hertz stress, 17.1×10^{8} N/m^2 (248 000 psi); maximum bending stress, 26.7×10^{7} N/m^2 (38 700 psi); speed, 10 000 rpm; temperature, 350 K (170^0 F); lubricant, superrefined naphthenic mineral oil.

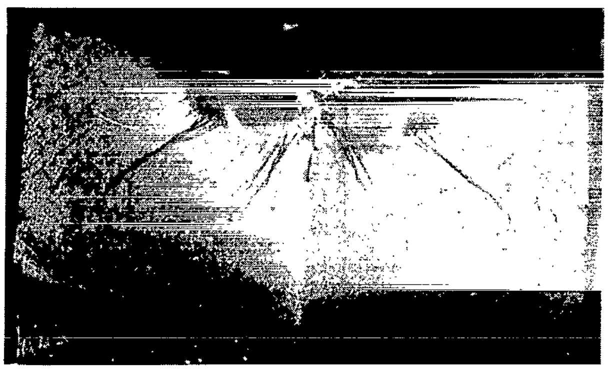


(a) Standard forged.

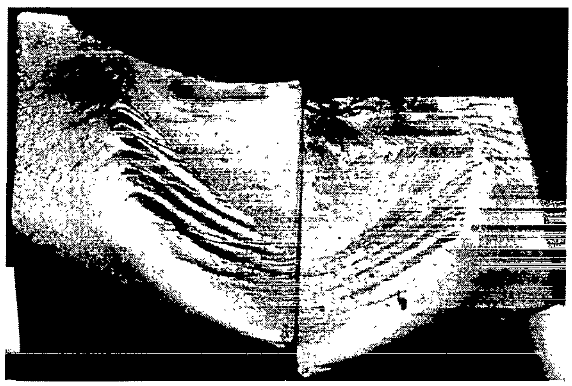


(b) Ausforged.

Figure 9. - Typical fatigue spall of vacuum-induction-melted, consumable-electrode, vacuum-arc-remelted (VIM-VAR) AISI M-50 gear teeth. Maximum pitch-line Hertz stress, 17.1×10^8 N/m^2 (248 000 psi); maximum bending stress at tooth root, 26.7×10^7 N/m^2 (38 700 psi); speed, 10 000 rpm; temperature, 350 K (170° F); lubricant, superrefined naphthenic mineral oil.

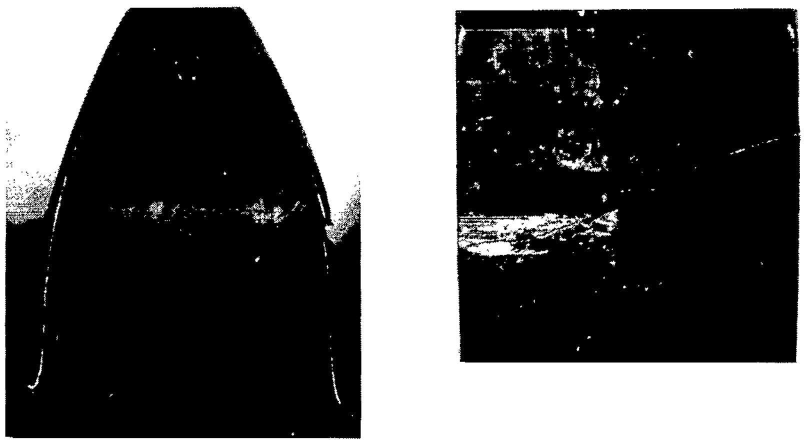


(a) Standard forged.

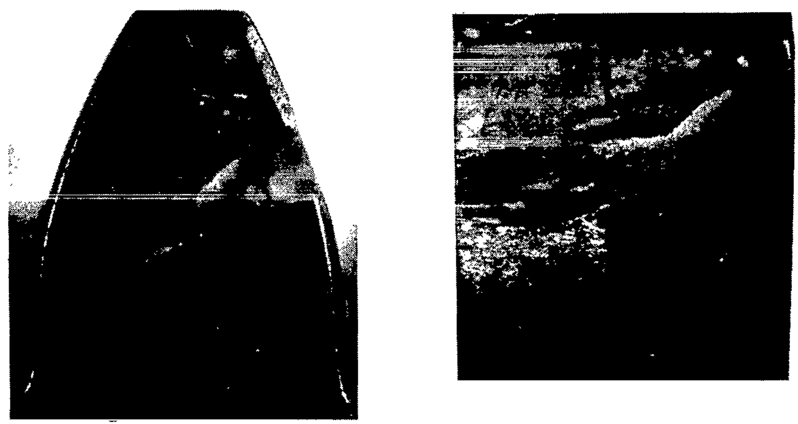


(b) Ausforged.

Figure 10. - Cross section of tooth fracture of vacuum-induction-melted, consumable-electrode, vacuum-arc-remelted (VIM-VAR) AISI M-50 gear teeth. Maximum pitch-line Hertz stress, 17.1×10^8 N/m^2 (248 000 psi); maximum bending stress at tooth root, 26.7×10^7 N/m^2 (38 700 psi); speed, 10 000 rpm; temperature, 350 K (170° F); lubricant, superrefined naphthenic mineral oil.



(a) Standard forged.



(b) Ausforged.

Figure 11. - Fatigue fracture of vacuum-induction-melted, consumable-electrode, vacuum-arc-remelted (VIM-VAR) AISI M-50 gear teeth. Maximum pitch-line Hertz stress, 17.1×10^8 N/m^2 (248 000 psi); maximum bending stress at tooth root, 26.7×10^7 N/m^2 (38 700 psi); speed, 10 000 rpm; temperature, 350 K (170° F); lubricant, superrefined naphthenic mineral oil.

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