ENGINEERING RESEARCH INSTITUTE
UNIVERSITY OF MICHIGAN
ANN ARBOR

Final Report

CARBURIZED FINAL-DRIVE PINION GEARS

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Project 2171

DETROIT ARSENAL, DEPARTMENT OF THE ARMY
CONTRACT NO. DA-20-089-ORD-36692
CENTER LINE, MICHIGAN

June 1955

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OBJECTIVE

The objective of this project was to determine the beneficial or detrimental effect of retained austenite in the case-hardened area of final-drive pinion gears made from 43BV15-grade steel.

ABSTRACT

A laboratory method which can be used for cooling parts to temperatures as low as -150°F is described.

A locked-torque testing arrangement, which was built for testing M-47 tank final-drive assemblies under input torques as high as 4,000 lb-ft and speeds as high as 2,000 rpm, are described.

An investigation is reported which shows the effect of following the normal quenching operation with a deep freezing treatment on the 43BV15-grade steel used in the M-47 tank final-drive pinion gears.

CONCLUSIONS

1. The addition of the deep-freezing operation to the normal heat treatment of the case-hardened 43BV15 gear steel does not affect the wear characteristics of this steel.

2. The metallographic examination indicates that no appreciable amount of retained austenite remains after the normal heat treatment of the case-hardened 43BV15 gear steel.

3. The results indicate that the deflections caused by the over-hanging gear mounting used on the M-47 tank final drive influence gear wear more than the deep-freezing operation investigated in this study. This particular final drive could be helped more by a redesign to eliminate the over-hanging output gear than by a change in the heat treatment of the pinion gear.

4. The metallographic examination indicates that the test gears were made from several different batches of steel.

RECOMMENDATIONS

1. It is recommended that the deep-freezing operation, proposed as a means of reducing the amount of retained austenite in the case-hardened 43BV15 gear steel, not be adopted.

2. It is recommended that the M-47 final drive be redesigned with bearings on each side of the output gear to prevent shaft deflection and to provide better tooth contact.

3. It is recommended that the steel for future gear-comparison tests be made from the same bar of steel to eliminate differences of grain size found in this investigation. It was understood that the gears made for

this test were to be of steel from the same bar but the results prove otherwise.

4. It is recommended that the radioactive method of measuring gear wear be considered in future gear-wear studies because of its ability to show total wear regardless of whether or not the wear is evenly distributed on the teeth. Furthermore, this method furnishes information about the rates of wear under varying loads and speeds with a high degree of accuracy while the test is in progress.

DESCRIPTION

An insulated box, shown in Fig. 1 was designed and constructed for the deep-freezing treatment. This box was insulated with Sil-O-Cell-C, silicon dioxide, insulation. The insulating properties of this insulation are excellent, 3 inches of Sil-O-Cell-C being equal to 11 inches of glass-wool insulation. This box was filled with Freon-11 trichloro monofluoro methane, to a height sufficient to cover the gear. A copper heat-exchanger tube was placed in the center of the box. The Freon-11 acted as a heat-transfer medium to transfer heat from the pinion gear to the liquid nitrogen which was poured into the copper heat-exchanger tube. A small blower with an electric heating coil was used to blow hot air into the heat-exchanger tube to prevent the temperature from going below the desired point.

A locked-torque testing fixture using two M-47 tank final-drive assemblies was designed and constructed. This fixture was designed for a maximum input torque of 4,000 lb-ft, and a maximum input speed of 2,000 rpm. A sketch of this fixture is shown in Fig. 2 and photographs in Figs. 28 and 29. The output flanges of the two final drives were connected by two Sier-Bath, size 4-1/2 couplings, and a floating shaft. The input shafts were connected in the following manner. The input shaft assembly No. 7721060, normally supplied with the M-47 tank final-drive assembly was replaced by shaft No. D68108. Retainer No. 5660143 was replaced by special bearing supports and shaft No. D68108 was inserted through this bearing support.

A special torque loading and adjusting shaft assembly was connected to these two input shafts. This arrangement is shown in the sketch of Fig. 2. The torque was adjusted by means of the two large plates mounted on this shaft which could be rotated relative to each other by means of the two large adjusting screws. A strain-gage torque meter was built on the long shaft. Painted slip rings were used to make possible the reading of

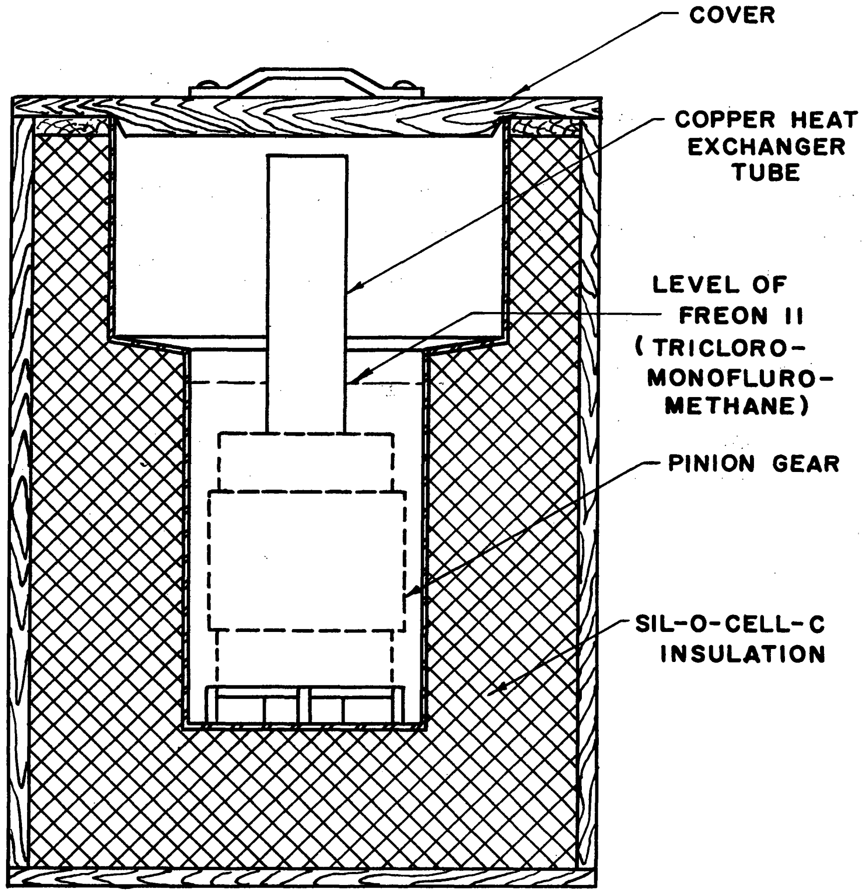


Fig. 1. Cold treatment box

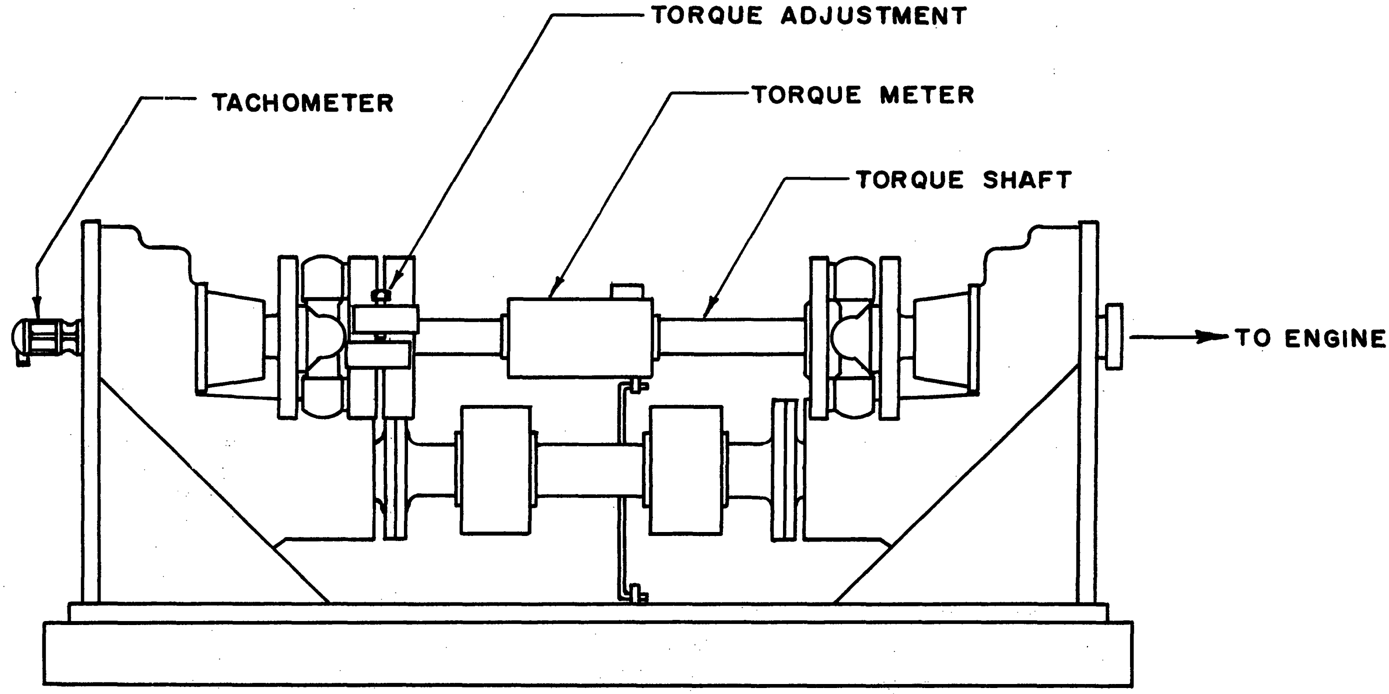


Fig. 2. Locked-torque test set up.

torque while running. An input shaft was connected to a Dodge 3/4-ton military truck engine. With this arrangement, the engine is called on to make up the friction losses only, not the full power going through the drives.

Thermocouples were installed in the gear cases so that the oil temperature of the oil leaving the pinion could be recorded. A tachometer generator was mounted on one end of the shaft to indicate accuractly the input shaft speed. Sound pickups, consisting of a piezoelectric crystal cartridge, were mounted on each case near the pinion gear. Holes were drilled in the final-drive housings so that measurements could be made at the center of the pinion gears without disassembly of the unit. The temperatures were indicated on a Brown automatic-balancing indicating-type potentiometer. The torque was indicated on a Baldwin Type M strain-gage indicator; the speed was indicated on a Type E-9 aircraft tachometer. The lubrication used in the final drives was SAE 30 Indolube oil made by Standard Oil Company.

PROCEDURE

The gears used in this test were received from American Gear and Manufacturing Company, Lemont, Illinois, after the carburizing operation. The case-hardened pinion gears were heated to 1550 to 1575°F and then quenched in oil with good agitation. This heat treatment, which is standard for this gear, had been found by previous work at the Detroit Arsenal to provide about 15% retained austenite in the case-hardened area of the gear teeth. Immediately following the heat treatment, the gears were degreased and placed in the cold-treating box. Thermocouples were placed at the pitch line of the gear teeth to indicate the gear temperature.

Prior to placing the gears in the cold-treating box, the Freon-11, trichloro monofluro methane, was cooled to -90°F by the addition of pieces of solid carbon dioxide. For pinions treated to temperatures above -90°F, sufficient solid carbon dioxide was added to the Freon to cool the Freon to the desired temperature. For temperatures below -90°F, liquid nitrogen was added to the copper heat-exchanger tube in the center of the gear to cool the Freon to the desired temperature. Temperature of the gear was recorded at 2-minute intervals and the cooling data were plotted in Fig. 4.

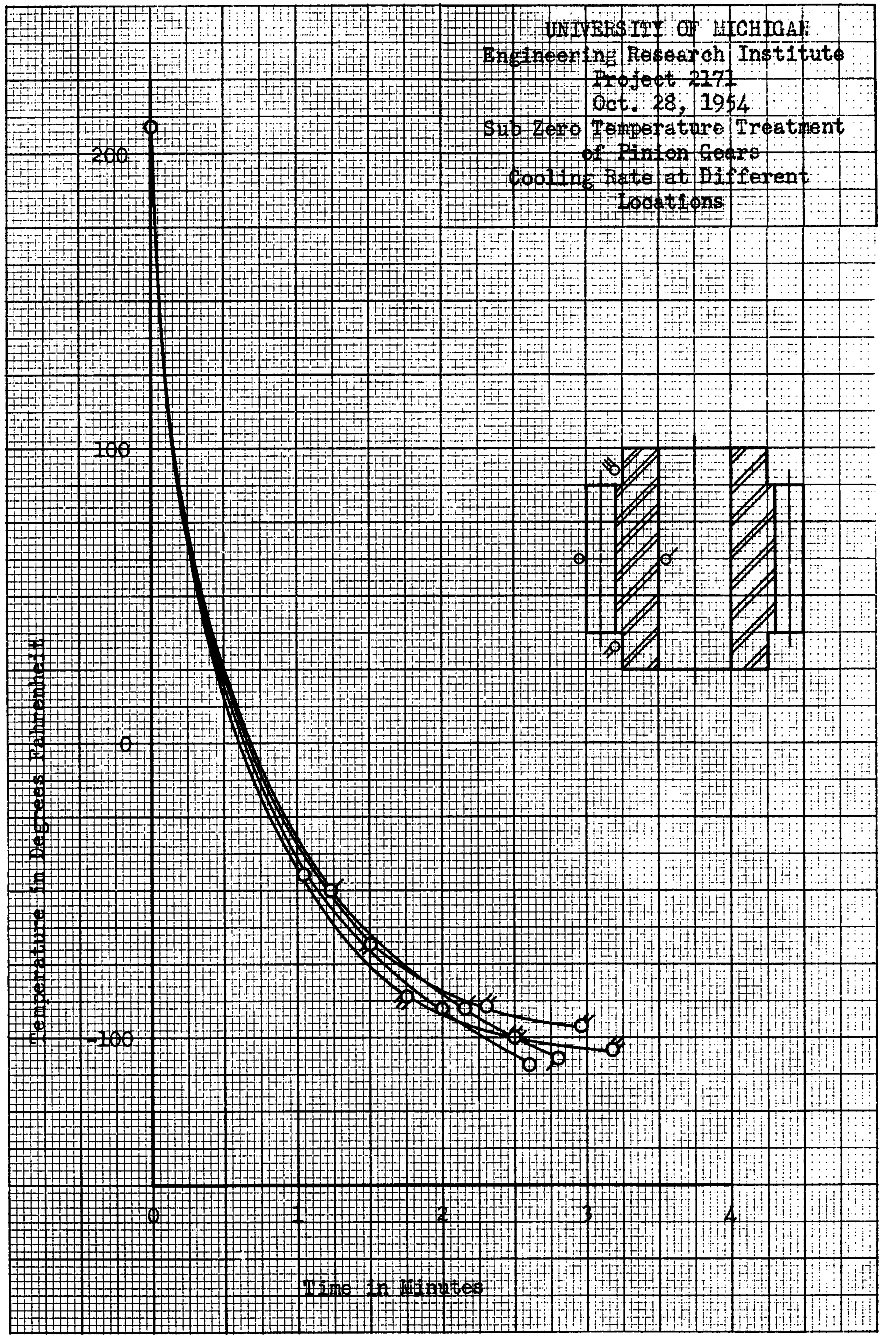
When the gear reached the desired temperature, the addition of liquid nitrogen was stopped. A small blower with an electric heating coil was used to force heated air into the heat-exchanger tube to regulate the temperature and to prevent overcooling. The gears were left in the cold-treating box for 15 minutes after the desired temperature was reached and then removed and allowed to warm up to room temperature. This procedure was followed until all the gears had been treated to the required low temperatures. The gears were then stress-relieved at 375°F. The gears were shipped back to American Gear and Manufacturing Company for final machining and copper plating. When the gears were finished, they were shipped back to the Dynamometer Laboratory at Willow Run Research Center. They were installed in the locked-torque testing fixture shown in Fig. 2 and run through the following tests.

The gears were run at 4,000 lb-ft input torque at 300 rpm for 50,000 cycles. Then the torque was changed to 600 lb-ft, the speed to 2,000 rpm, and the system run for 50,000 cycles. This procedure was repeated until a total of 1,000,000 cycles was run on each pinion gear. In addition, two sets of gears treated to -130 and -150°F, respectively, were run an additional 1,000,000 cycles making a total of 2,000,000 cycles on these two pinions.

Following the above load test, one tooth was cut from each of the final-drive pinions by means of a rubber wheel while the gear was kept cool by the use of a sufficient amount of cooling fluid. This tooth was then broken in the center and a section of it mounted and prepared for the metallographic examination.

The pinion gear was measured at the pitch line in the center of the tooth by means of a micrometer measuring over balls. The measurement was made at the same location each time. The temperature varied greatly during the test; therefore, it was necessary to determine the measurement at several temperatures and to establish a temperature correction curve. All measurements were then corrected to the same temperature. The micrometer readings were converted to actual gear wear by the calculations shown in the Appendix.

A preliminary investigation of the best location for the gear thermocouples was made. Four thermocouples were attached to the pinion gear as shown in the sketch in Fig. 3. The gear was heated to 212°F and then cooled to -100°F. The cooling curves for the four thermocouples are shown in Fig. 3. It was decided, from this information, that the thermocouple attached at the pitch line of the gear tooth would best indicate the gear temperature. This location was used in all the deep-freezing treatments.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Oct. 28, 1954
Sub Zero Temperature Treatment
of Pinion Gears
Cooling Rate at Different
Locations
Temperature in Degrees Fahrenheit
Time in Minutes
200
100
0
-100
0
1
2
3
4

Fig. 3.

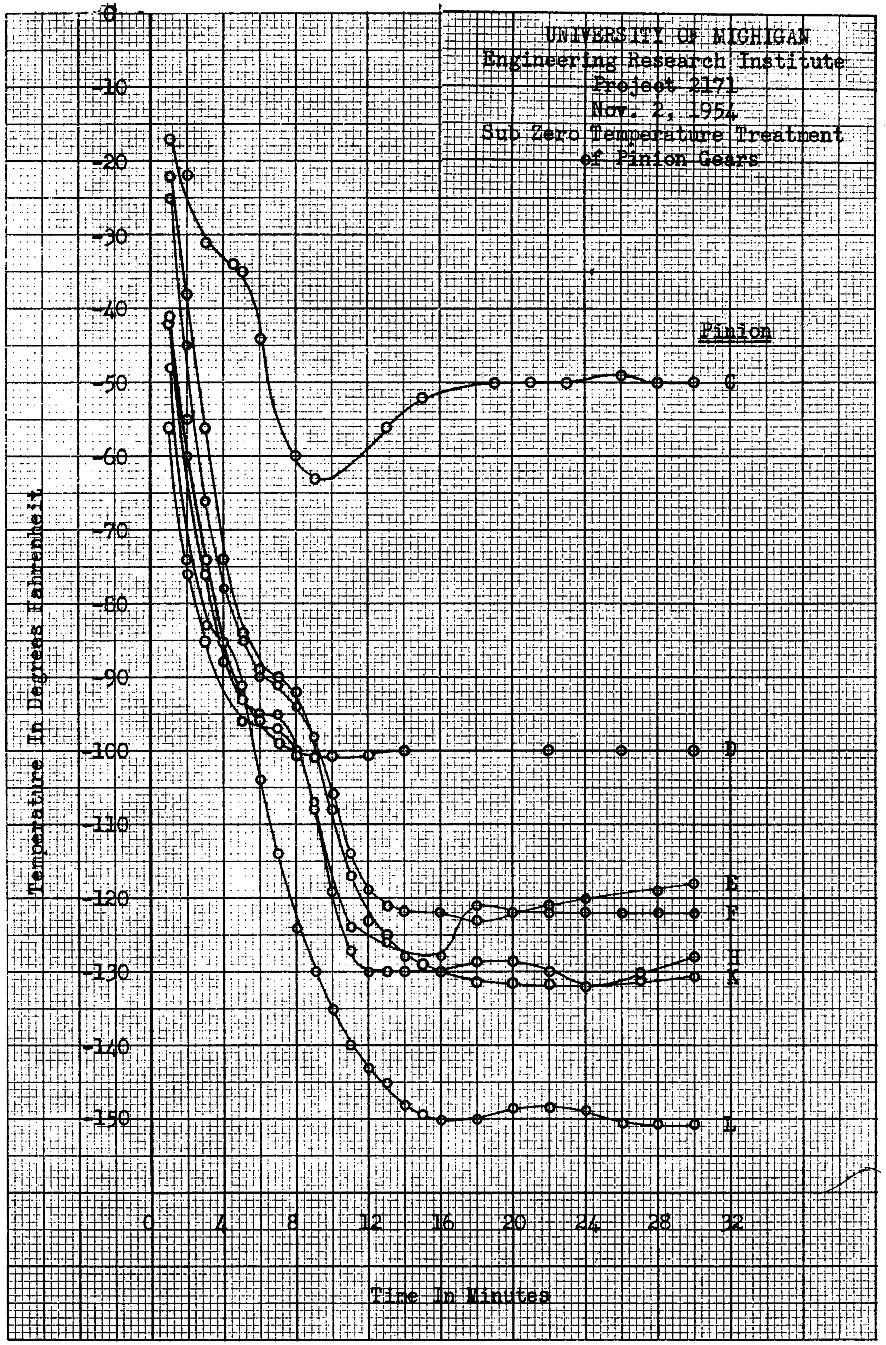

UNIVERSITY OF MICHIGAN
Engineering Research Institute
Project 2171
Nov. 2, 1954
Sub Zero Temperature Treatment
of Pinion Gears
Pinion
C
D
E
F
H
K
L
Temperature In Degrees Fahrenheit
Time In Minutes
0
-10
-20
-30
-40
-50
-60
-70
-80
-90
-100
-110
-120
-130
-140
-150
0
4
8
12
16
20
24
28
32

Fig. 4.

RESULTS OF WEAR TESTS

Inspections after the low torque runs disclosed that the wear pattern was evenly distributed across the face of the gear teeth. Inspections after the high torque runs disclosed a wear pattern shifted toward the side of the large gear on which the bearings were located. This shift of the wear pattern is caused by deflection of the shaft on which the large gear is mounted. This deflection prevents proper meshing of the gears resulting in wear which is influenced more by the mounting than by the deep-freezing treatment. The wear patterns of the gears are shown in Figs. 5 through 13.

The following table presents the wear data obtained in the tests;

		Wear at Pitch Line	
Pinion	Cold Treatment, °F	After 10^6 Cycles, in.	After 2×10^6 Cycles, in.
1	None	0.0006	
2	None	0.0009	
B	None	0.0018	
C	-50	0.0012	
D	-100	0.0006	
E	-120	0.0012	0.0018
F	-120	0.0006	
H	-130	0.0006	
K	-130	0.0005	
L	-150	0.0007	0.0013

Fig. 5. Wear pattern after 10^6 cycles.

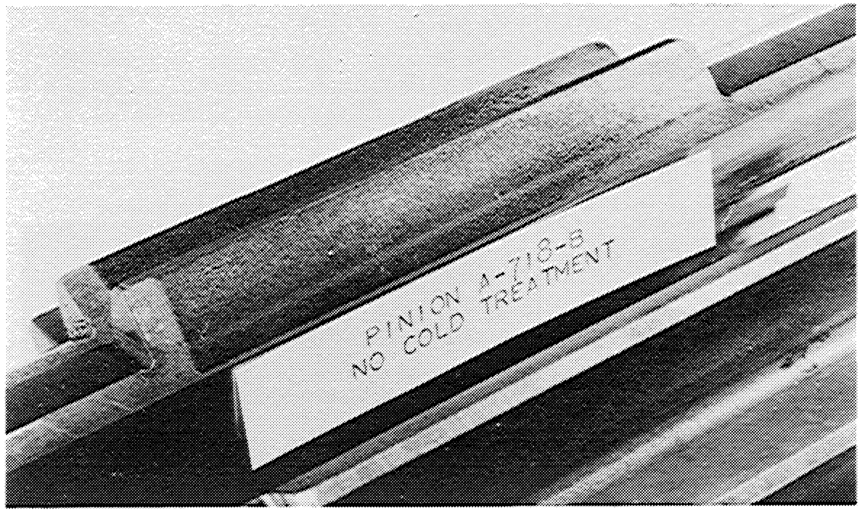


Fig. 6. Wear pattern after 10^6 cycles.

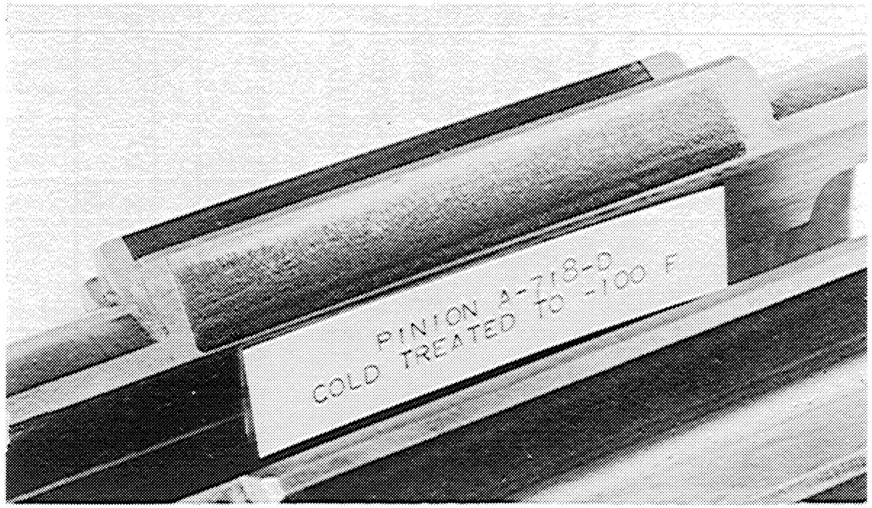


Fig. 8. Wear pattern after 10^6 cycles.

Fig. 7. Wear pattern after 10^6 cycles.

Fig. 9. Wear pattern after 2 x 10^6 cycles.

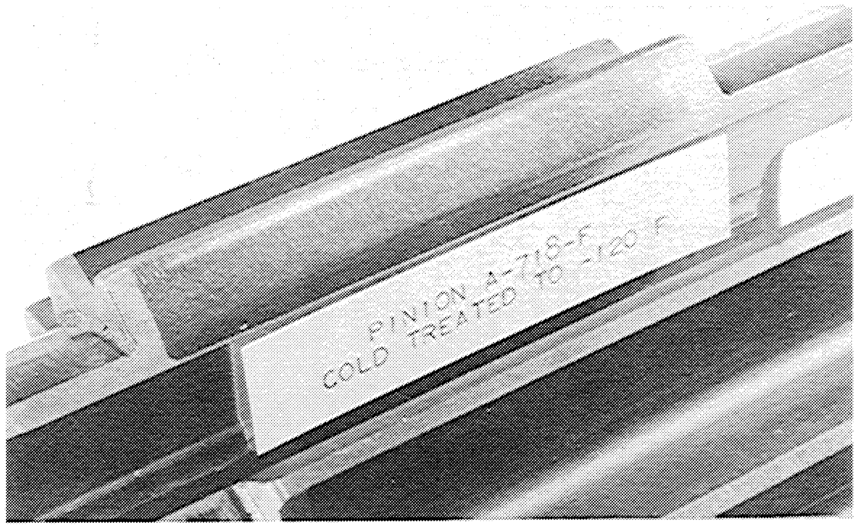


Fig. 10. Wear pattern after 10^6 cycles.

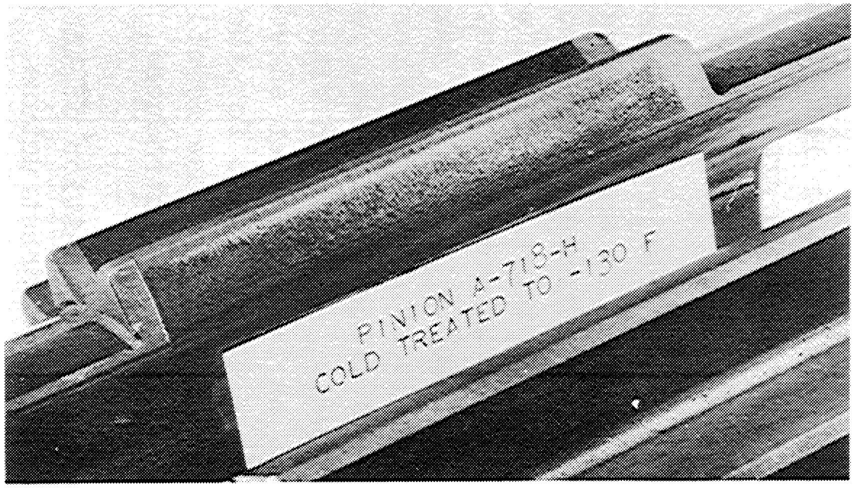


Fig. 11. Wear pattern after 10^6 cycles.

Fig. 12. Wear pattern after 10^6 cycles.

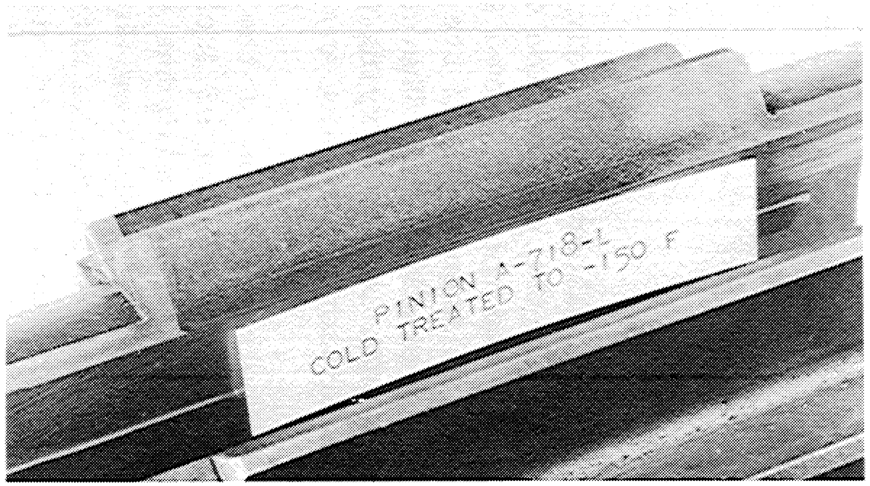


Fig. 13. Wear pattern after 2 x 10^6 cycles.

It must be concluded from the above results that the deep-freezing treatment does not influence the wear characteristics of the pinion gears made from 43BV15 steel.

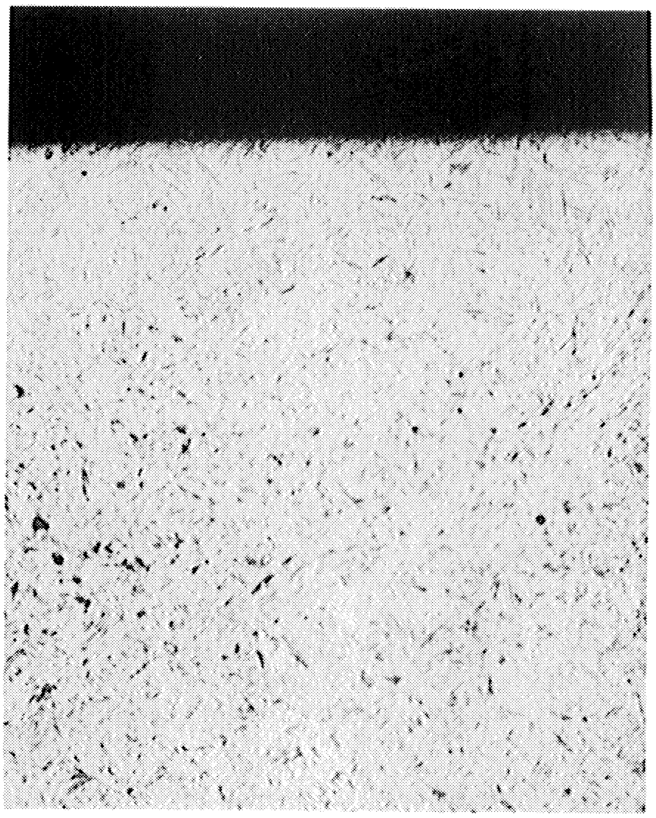
METALLOGRAPHIC EXAMINATION

A metallographic study was made of gear tooth sections from the nine gears. In the preparation of the samples, a tooth was cut from each of the gears and then fractured at roughly the midpoint. One of the fractured ends was then cut from the tooth and the fracture cross section then prepared for examination. The cutting out of the gear tooth and the removal of the 3/4-inch length carrying the fracture were done under carefully controlled conditions, avoiding any possible overheating of the section.

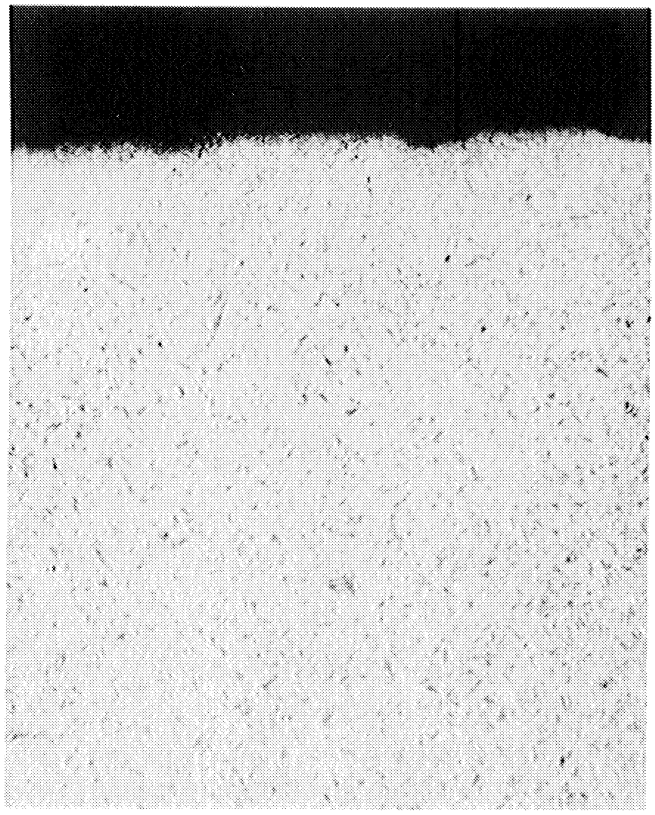
The examination of the polished but unetched sections showed the presence and distribution of inclusions to be about the same for steel of each of the gear teeth with the exception of E(-120°F). E(-120°F) showed, in addition to the inclusions which were present in the other gear teeth, what appears to be zirconium nitride. This would indicate that gear E was made from a different heat of steel than was used for the other eight gears. It may or may not be significant that gears E(-120°F) and F(-120°F) were both given sub-zero treatments at -120°F, and the wear loss for E(-120°F) is roughly double the wear loss for F(-120°F). E(-120°F) and F(-120°F) also showed differences in grain size and in surface hardness as measured on the tip of the gear teeth.

A difference in the smoothness of the teeth faces was also observed. Figures 14 and 15 illustrate the nature of the variation. Visual examination confirmed the variations in surface of the gear teeth. As with the presence of the added inclusion in E(-120°F) the presence of the pitted or uneven surface may or may not be significant. B(std) and C(-50°F) probably showed the maximum unevenness in the surface while 1(std) showed the least or the smoothest surface. E(-120°F) approaches very closely 1(std) in surface smoothness, yet B(std), C(-50°F), and E(-120°F) showed the greatest wear. Comparison with F(-120°F), which received the same sub-zero treatment as E(-120°F) but showed only a slightly pitted or uneven surface, indicates a 2 to 1 ratio for the wear for uneven or pitted surface as compared to the wear for the relatively smooth surface. In the case of E(-120°F), a second factor was introduced, as previously discussed.

The examination of the etched section failed to reveal any marked differences in microstructure. Representative microstructures as found at 0.003 to 0.004 inch below the surface are shown in Figs. 16 through 24.



250X Fig. 14.



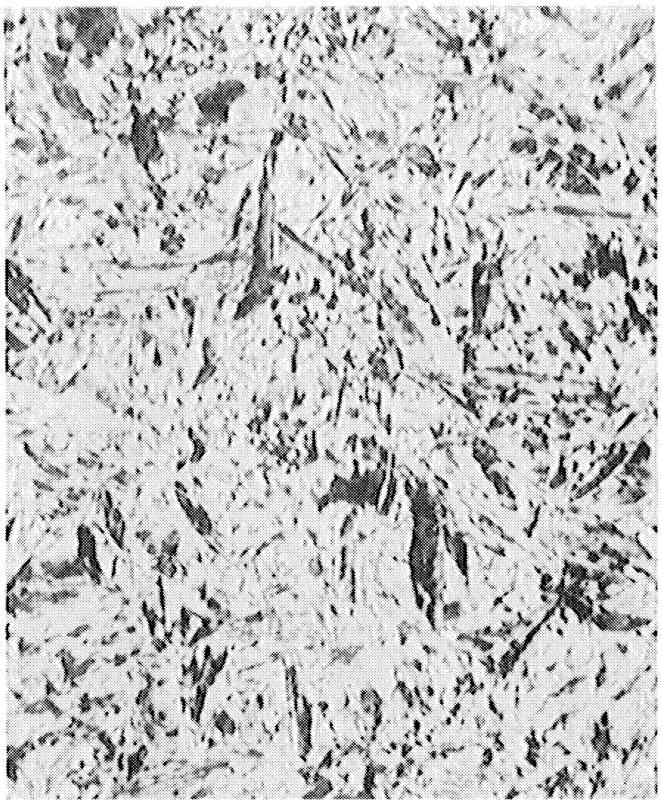
250X Fig. 15.

Figs. 14-15. Cross sections cutting through face of gear teeth; illustrations of smoothness and unevenness or pitting of faces of the different gears; sections subjected to light etch.

Figs. 16-19. Typical microstructures for hardened section of gear teeth from gears A, B, C, and D. All sections are located at .0025 to .0030 inch below tooth face. Gears 1 and B were not subjected to sub-zero temperature treatments. Gears C and D were treated at -50 and -100°F.

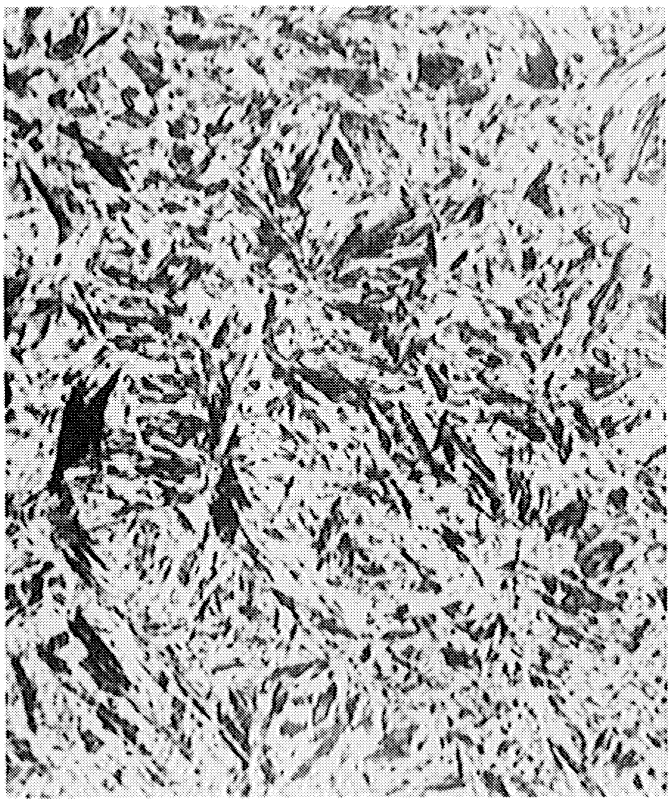
1000X Etch Nital

Fig. 16A.



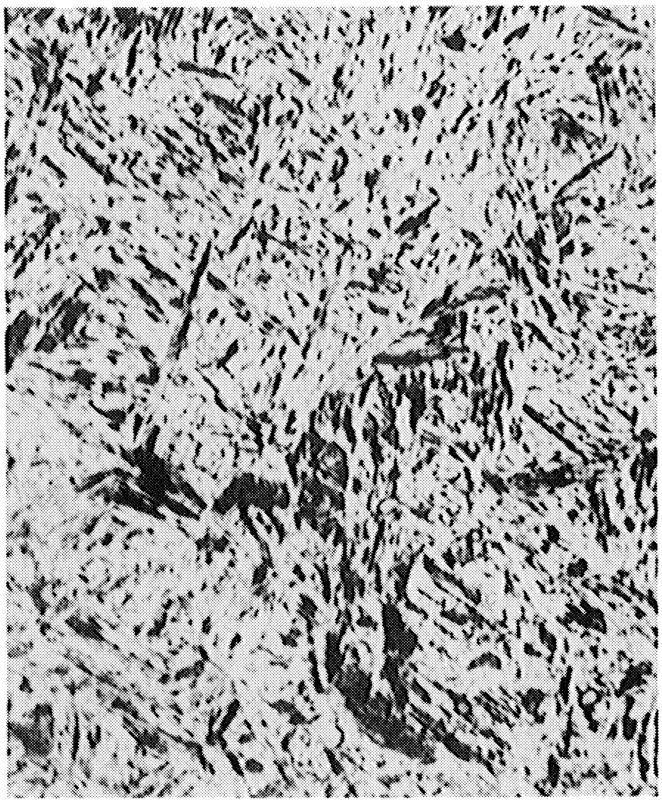
1000X Etch Nital

Fig. 17B.



1000X Etch Nital

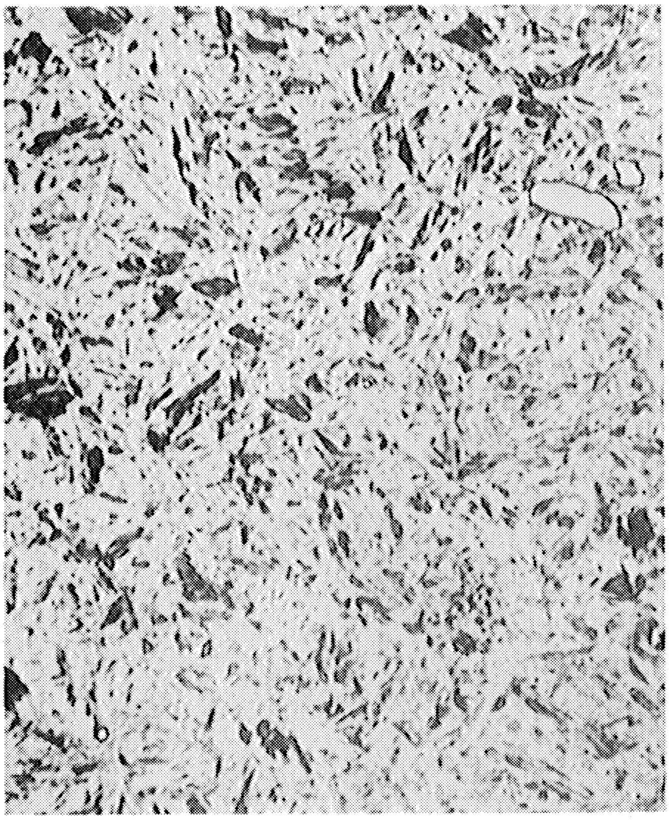
Fig. 18C.



1000X Etch Nital

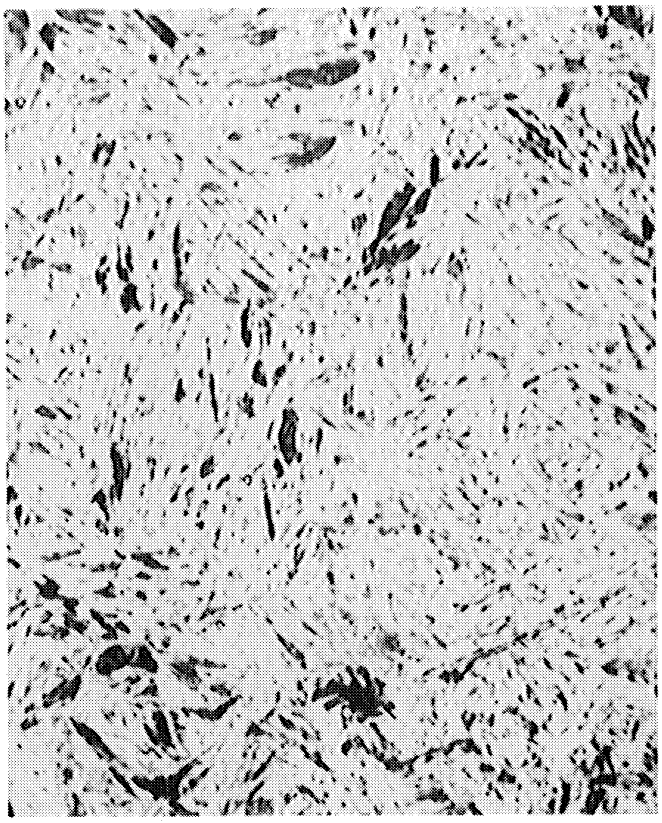
Fig. 19D.

Figs. 20-23. Typical microstructures for hardened section of gear teeth from gears E, F, H, and K. All sections are located 0.0025 to 0.0030 inch below tooth face. Gears E and F were subjected to sub-zero temperature treatments at -120°F, H and K at -130°F.



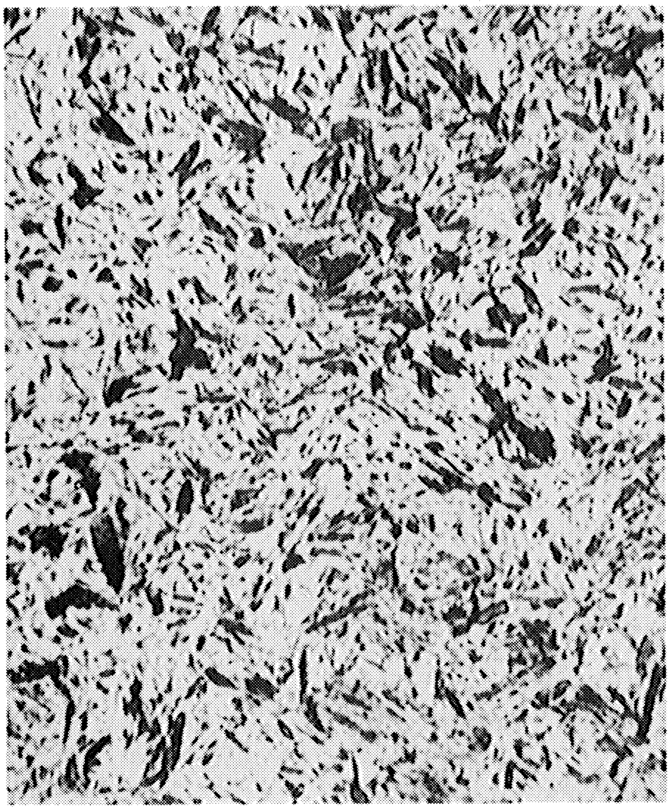
1000X Etch Nital

Fig. 20E.



1000X Etch Nital

Fig. 21F.

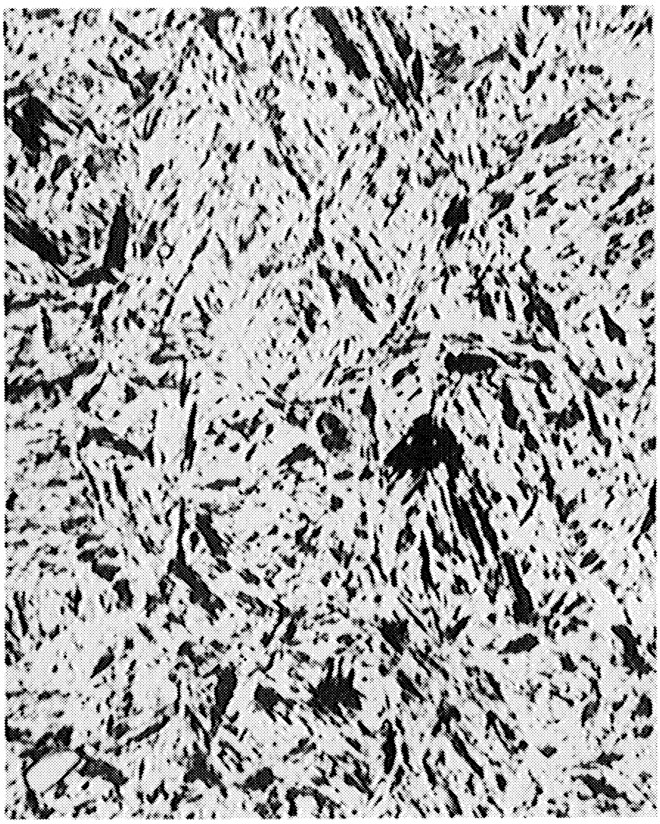


1000X Etch Nital

Fig. 22H.

1000X Etch Nital

Fig. 23K.



1000X Etch Nital

Fig. 24. Typical microstructure for hardened section of tooth from gear L section located 0.0025 to 0.0030 inch below tooth face. L was subjected to sub-zero temperature treatments at -150°F.

Coarseness or fineness or variations in grain size (though limited) appear to be about the only observable differences. 1(std) and B(std) differ slightly in grain size and in fineness of the martensite pattern. C(-50°F), the first of the sub-zero-treated steels, shows a slightly smaller grain size with a coarser martensite pattern than 1(std) or B(std). The pattern reverses again with D(-100°F). The small grain size variations can only be accounted for on the basis of the oil-quench treatment or the original hardening. It will be observed that E(-120°F), F(-120°F), H(-130°F), and K(-130°F) sub-zero treatments at -120 and -130°F again show small grain size variations and fineness or coarseness of martensite pattern. L(-150°F) shows a well developed martensite pattern not unlike D(-100°F). These small variations show no direct correlation with the wear losses.

A check was made of surface hardness at the tip of the gear tooth and also of the hardness at varying distances below the surface. Using Rockwell 15N and 30N, the values listed below were found for the nine gear teeth at the tip surface.

	15N		30N
L, -150°F	90.9	B, std	77.7
C, -50°F	90.0	L, -150°F	77.7
E, -120°F	89.8	E, -120°F	77.7
B, std	89.7	C, -50°F	76.9
1, std	89.5	F, -120°F	76.5
F, -120°F	89.0	H, -130°F	75.8
H, -130°F	89.0	1, std	75.5
K, -130°F	88.3	K, -130°F	75.4
D, -100°F	88.3	D, -100°F	75.3

The hardness values, whether Rockwell 15N or 30N consistently place B(std), C(-50°F), L(-150°F), and E(-120°F) in the top bracket. K(-130°F) and D(-100°F) fall in the bottom bracket. B(std) and L(-150°F) represent the extremes in treatment. B(std) had no sub-zero treatment; L(-150°F) was treated at -150°F following the quench. C(-50°F) and E(-120°F) represent almost as wide extremes in treatment, C(-50°F), a -50°F treatment and E(-120°F), a -120°F treatment. K(-130°F) with minimum hardness approaches the maximum sub-zero treatment -130°F against -150°F for L(-150°F). The hardness values, it would appear, were controlled to as great a degree, if not greater, by the initial quench rather than by the sub-zero treatments.

A hardness penetration survey using the U P numbers as determined with a 50-gram load generally confirmed the order of hardness as determined with the Superficial Rockwell Hardness Test. Figure 25 shows the 50-gram-load impression (diamond pyramid) at depths from roughly 0.002 to 0.015 inch and 250 magnifications for five of the gear teeth. While three of the four gears falling in the high hardness group show high wear, the fourth L(-150°F) falls in the low wear group. As previously pointed out, other factors, particularly surface smoothness or unevenness probably enter into the picture for these four gears. Considering K(-130°F) and D(-100°F), gear teeth with minimum hardness and low wear losses both showed only slight surface unevenness. It should be pointed out that the 15N and 30N values for K(-130°F) and D(-100°F) converted to Rockwell are all below the specified 58 minimum.

McQuaid Ehn Austenitic Grain Size

Gears E(-120°F), C(-50°F), H(-130°F) 6-8
E differs from C and H in that it shows zirconium addition.

Gears B(std), F(-120°F), D(-100°F) 3-6

Gears 1(std), K(-130°F), L(-150°F) 4-6

Difference between B, F, D, and 1, K, and L not marked but 1, K, and L appear slightly coarser than B, F, and D.

McQuaid Ehn grain size is normally shown at 100X but photomicrographs shown are at 250X for clarity.

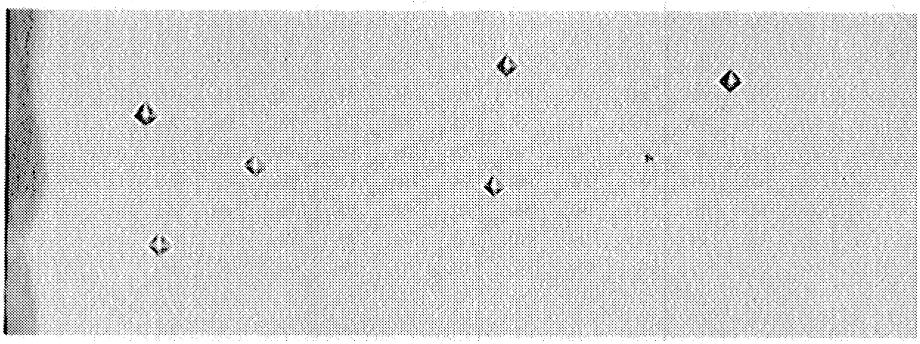
The results of the metallographic examination, supplemented by hardness tests, may be summarized as follows:

1. The surface of the gear tooth varies in smoothness from one gear to another. Pitting of the surface of some of the gears is observed readily under visual examination.

2. One gear E(-120°F) showed what is probably zirconium nitride in addition to the usual inclusions indicating that the steel used in making this gear was from a different heat than that used for the remaining gears.

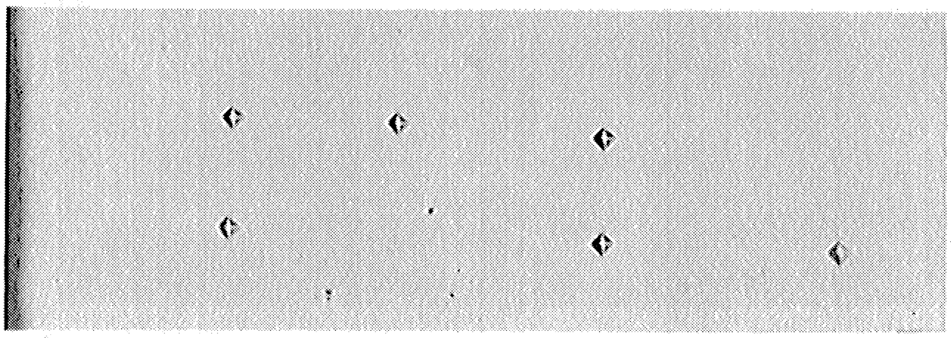
3. Microstructure variations were small in degree and limited to grain size and coarseness or fineness of the martensite pattern. These variations must be associated with the original quenching treatment rather than with the subsequent sub-zero temperature treatments.

4. Hardness variations of the order of 2.5 Rockwell 15N or 30N



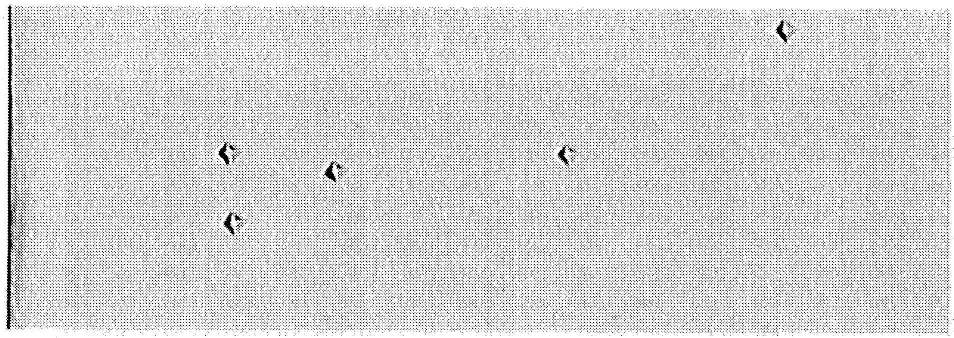
L

250X



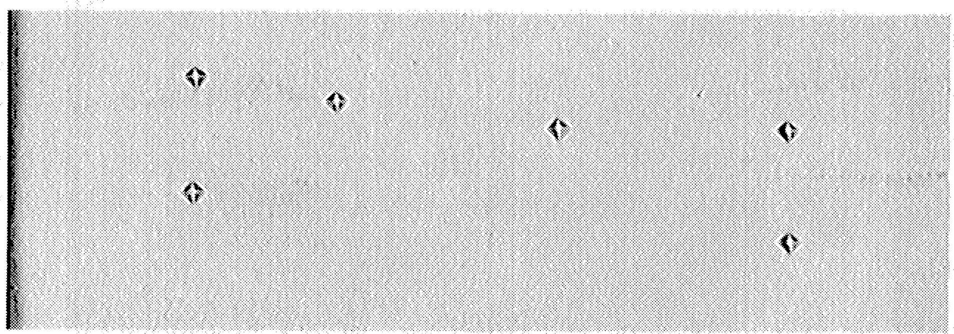
B

250X



D

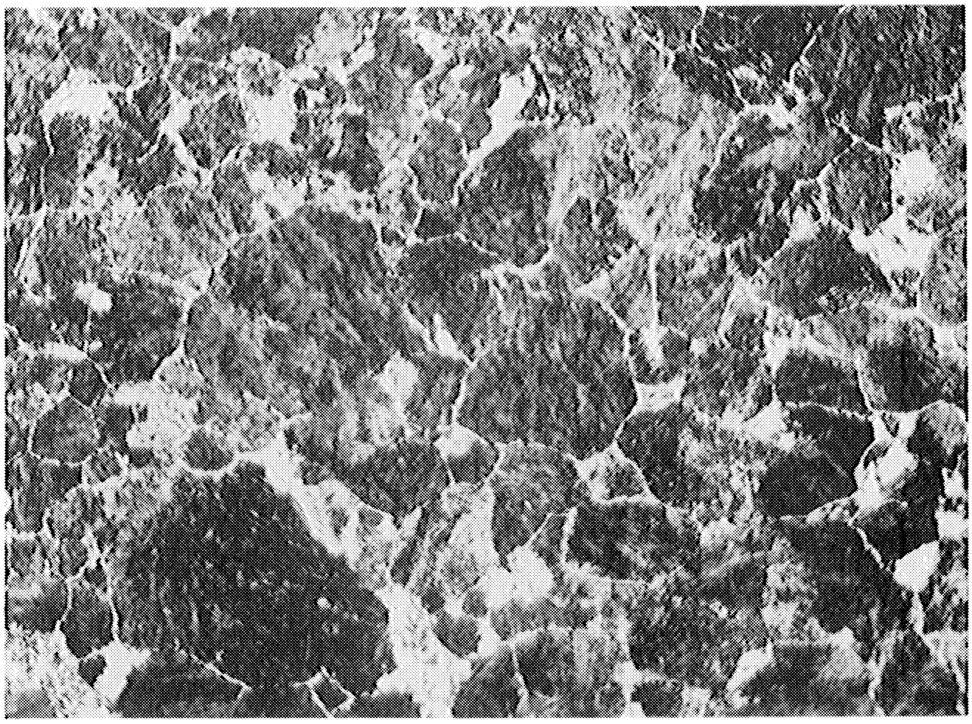
250X



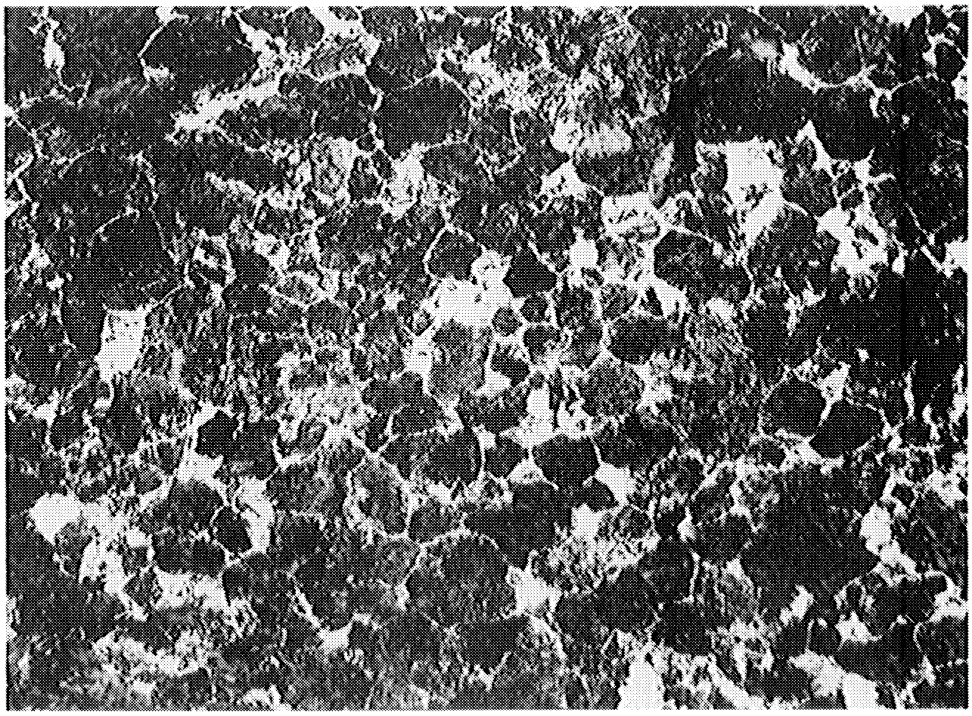
E

250X

Fig. 25. Subsurface hardness as indicated by VPH (diamond pyramid) impressions using 50-gram load; impressions made at 0.002 to 0.015 inch below surface sections from teeth from L, B, E, and D.



250X Fig. 26. Gear B(std). Etch Nital



250X Fig. 27. Gear H(-130°F). Etch Nital

Figs. 26-27. Photomicrographs showing austenitic grain size of McQuaid Ehn grain size samples of gear steels H and B.

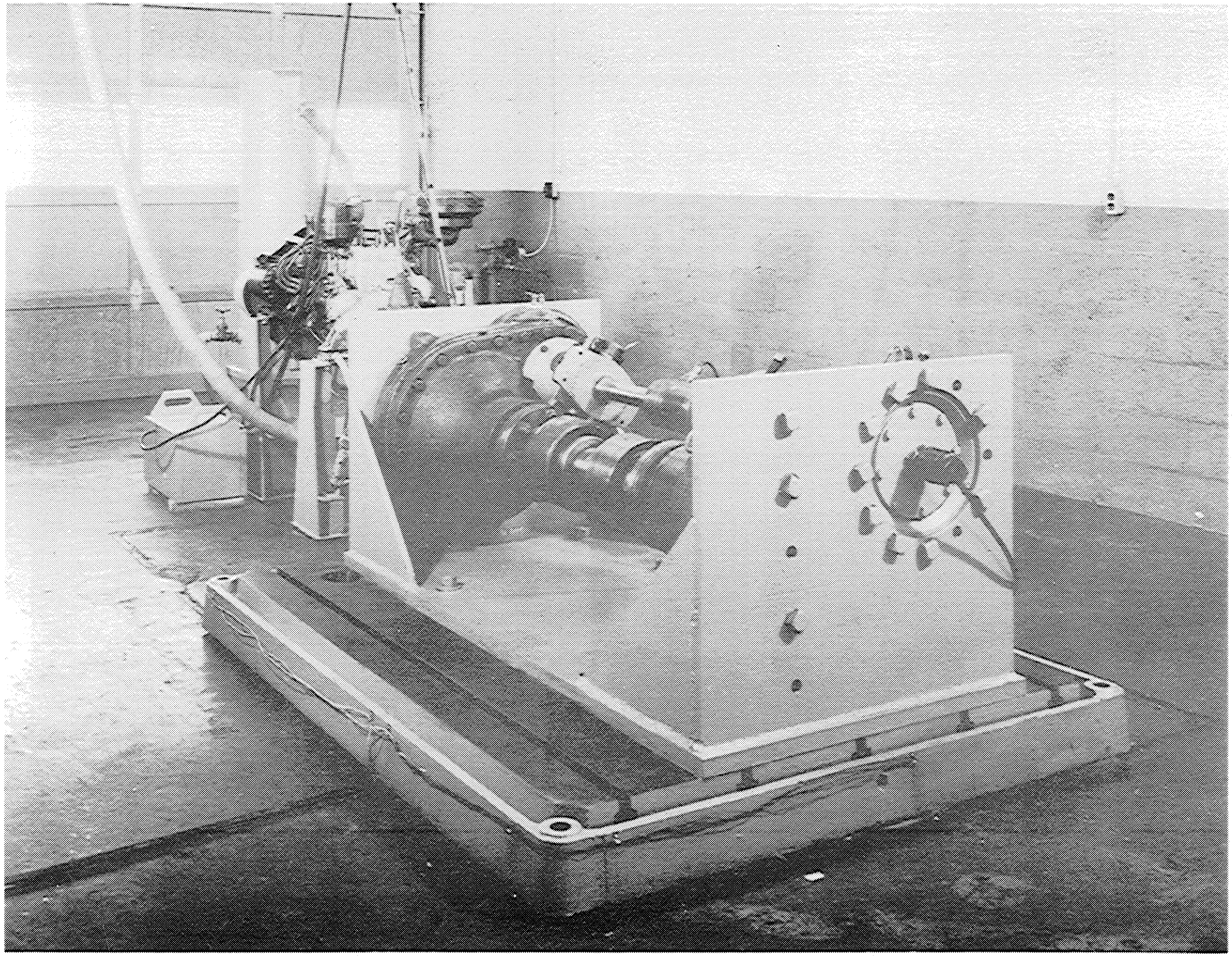


Fig. 28. Test setup.

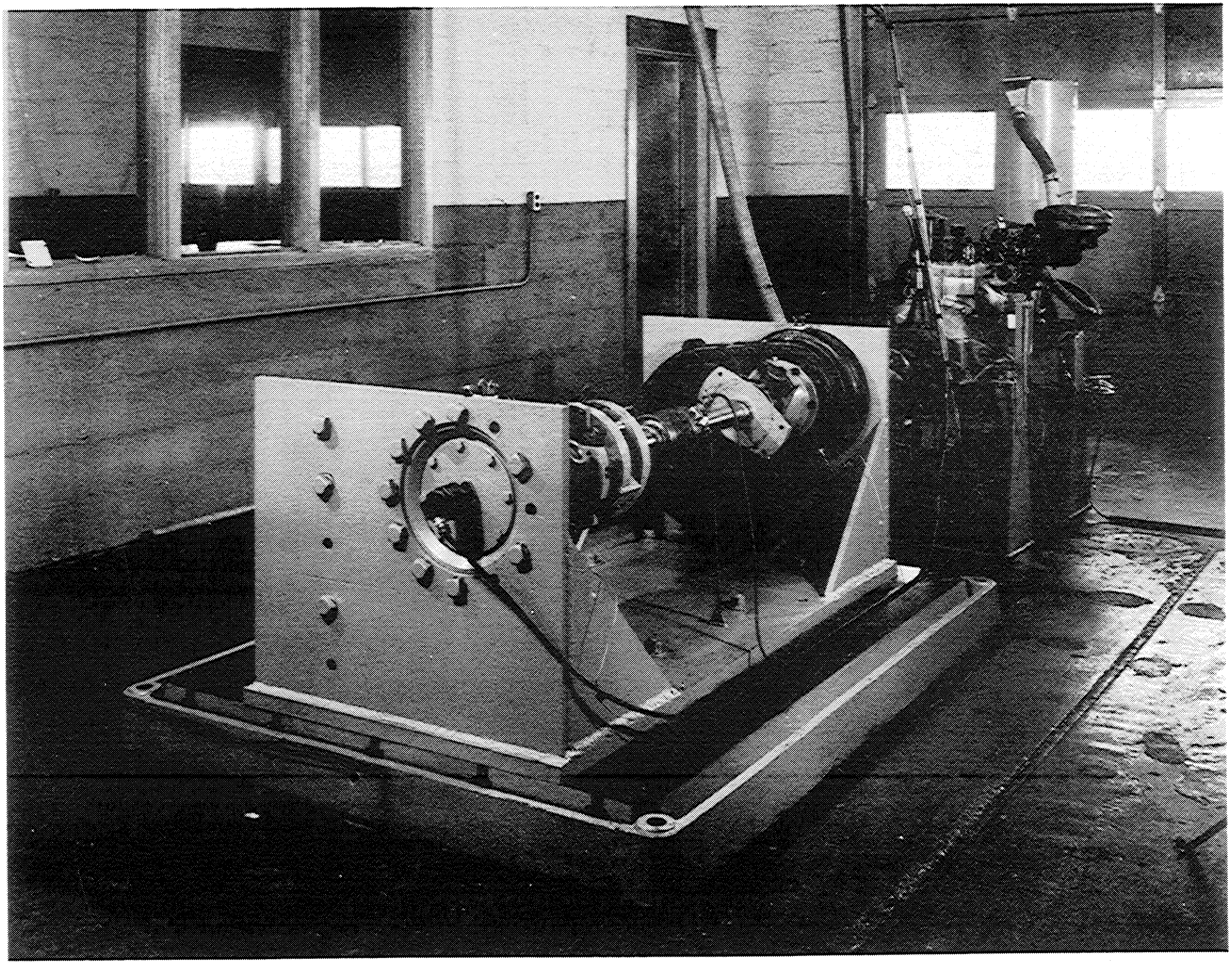


Fig. 29. Test setup.

were observed at the tip of the gear teeth. While these hardness variations can be roughly correlated with the wear losses, that is high wear for upper hardness range and low wear for lower hardness range, there are sufficient deviations to make the drawing of any conclusion questionable. Sub-surface hardness in general conforms to the order of surface hardness.

5. It must be concluded from the metallographic examination that the normal heat treatment does not leave an appreciable amount of retained austenite in the 43BV15 case-hardened steel gear. If the exact percentage is desired it would be necessary to make x-ray diffraction examinations of the treated specimens.

APPENDIX

PIN MEASUREMENT OF EXTERNAL INVOLUTE SPUR GEARS*

Gear Set No. 1, Pinion No. 1

No. of teeth	$N = 17$
Diametral pitch	$P = 4$
Main pressure angle	$\phi_M = 25°$
Measurement over pins uncorrected	$W' = 5.0951$ in.

Measurement before test at 68°F

Pos. 1 .1960

Pos. 2 .1955

Average $P_{BT} = .19575$ at 68°F

Measurement after 1,000,000 rev at 73°F

Pos. 1 .19525

Pos. 2 .19450

Average $P_{AT} = .194875$ at 73°F

Correction to 68°F = -.00012

Average P_{AT} at 68°F = .194755

$\Delta W = P_{BT} - P_{AT} = .000995$

$W = W' - \Delta W$

$= 5.0951 - .000995$ $\qquad W = 5.094105$

Diameter of pins $\qquad d_{pin} = 0.4375$

Calculated Gear Dimensions

Pitch diameter $2R = N/P = 17/4$	4.2500000 in.
Base diameter $d_b = 2R\cos\phi_M$	3.8518082 in.
(Standard) base space semiangle $\hat{\sigma}_b^* = \frac{\pi}{2N} - \text{inv}\,\phi_M$	.0624245 rad
Distance between pin centers $W - d_{pin} = 5.094105 - .4375$	4.6566050 in.
$\text{Sec}\,\frac{90°}{N}$	1.0042841

$$Ev\theta_A = \frac{W - d_{pin}}{d_b} \times \text{Sec}\,\frac{90°}{N}$$

*Dr. Werner F. Vogel, "Involutometry and Trigonometry," Michigan Tool Company.

$= \dfrac{4.65\ 66050}{3.85\ 18082} \times 1.0042841$ 1.2141192

By Interpolation From Main Table Find

$\widehat{\theta}_A$ auxiliary polar angle .0855463 rad

$\phi = 34.55$ $Ev\theta = 1.21\ 41351$ $Ev\theta_A = 1.2141192$

$\phi = 34.54$ $\underline{Ev\theta = 1.21\ 39892}$ $\underline{Ev\theta = 1.2139892}$

$\Delta Ev\theta = .0001459$ $\Delta Ev\theta' = .0001300$

$$\widehat{\theta}_A = .08\ 54726 + \frac{1300}{1459} \times 827$$

$$\widehat{\theta}_A = .08\ 54726 + 737$$

$\dfrac{d_{pin}}{d_b}$ .1135830 rad

Base space semiangle

$$\widehat{\sigma_b} = \frac{d_{pin}}{d_b} - \widehat{\theta}_A$$

$= .1135830 - .0855463$ .0280367 rad

$\widehat{\Delta_T} = \widehat{\sigma}_b - \widehat{\sigma}_b{}^*$

$= .02\ 80367 - .0624245$ -.0343878 rad

Deviation from Standard Tooth Thickness on the Rolling Circle

$$\Delta t = 2R\ \widehat{\Delta_T}$$

$= 4.2957(-.0343878)$ -.1477 197 in. (oversize)

Inches Wear of Tooth Arc Along Rolling Circle

$$\Delta t_w = \Delta t_s - \Delta t$$

(Δt_s = tooth modification)

$= .1483519 - .1477197$ .0006322 in.

There is a wear of .0006 inch per 1,000,000 revolutions