AD NUMBER
AD855761
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies and their contractors; Administrative/Operational Use; APR 1969. Other requests shall be referred to Army Aviation Materiel Labs., Fort Eustis, VA.**
AUTHORITY
USAAMRDL ltr 23 Jun 1971

AD855761

AD

USAAVLABS TECHNICAL REPORT 69-11

EVALUATION OF ADVANCED GEAR-FORGING TECHNIQUES

By

Lester R. Burroughs

Paul C. FitzGerald

April 1969

U. S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA

CONTRACT DAAJ02-67-C-0014
SIKORSKY AIRCRAFT
DIVISION OF UNITED AIRCRAFT CORPORATION
STRATFORD, CONNECTICUT

[redacted]

76

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission, to manufacture, use, or sell any patented invention that may in any way be related thereto.

Disposition Instructions

Destroy this report when no longer needed. Do not return it to the originator.

DEPARTMENT OF THE ARMY
HEADQUARTERS US ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA 23604

This report represents a part of the effort of a continuing program to explore and derive advanced technology for the design of power transmission systems. Presented herein are the results of a contractual effort to evaluate the static bending fatigue strength of gears manufactured from forgings forged with integral teeth. The results of the effort indicate that gears manufactured from such forgings have potential for significantly greater bending fatigue strength than conventionally cut and ground gears. This particular effort was limited to single tooth fatigue testing. A follow-on program has been initiated to dynamically test gears manufactured by the advanced forging methods.

This command concurs with the findings of the contractor.

Task 1G162204A01410
Contract DAAJ02-67-C-0014
USAAVLABS Technical Report 69-11
April 1969

EVALUATION OF ADVANCED GEAR-FORGING TECHNIQUES

Sikorsky Engineering Report 50560

By

Lester R. Burroughs
Paul C. FitzGerald

Prepared by

Sikorsky Aircraft
Division of United Aircraft Corporation
Stratford, Connecticut

U.S. ARMY AVIATION MATERIEL LABORATORIES
FORT EUSTIS, VIRGINIA. 23604

[redacted]

SUMMARY

The results of a gear fatigue research program, which extended over an 18-month period, are reported herein. The purpose of this research effort was to compare both the fatigue and static bending strengths of spur gear teeth manufactured by various advanced forging processes and one conventional forging process.

All of the advanced forging processes used a similar method of fabrication, in that they incorporated high energy rate forging techniques. The types of press and design of the dies were different for the three advanced processes. However, the as-forged gear blanks were similar except for some variations in the flash formation.

On the basis of the results obtained, it is concluded that spur gears fabricated from forgings which produce integrally forged teeth have higher fatigue strengths than conventionally cut and ground gears made from pancake forgings. Increases in endurance limit were found to vary from 24 percent to 44 percent when comparing the integrally forged gear teeth with the conventionally produced gears.

FOREWORD

This report covers a comparative evaluation of spur gears manufactured from conventional and high energy forging techniques. The high energy forgings produced gear blanks with integrally forged teeth. The evaluation included both single tooth static and fatigue tests. The project was conducted during the 14-month period from August 1, 1967, to September 30, 1968, for the U.S. Army Aviation Materiel Laboratories (USAAVLABS) under Contract DAAJ02-67-C-0014 (Task 1G162204A01410).

USAAVLABS technical direction was provided by Mr. Leonard M. Bartone, Chief, Mechanical Systems Branch, Aircraft Systems and Equipment Division.

The program was conducted at Sikorsky Aircraft under the technical supervision of L. R. Burroughs, Supervisor, Mechanical Systems Section. Principal investigators for the program were P. C. FitzGerald and R. Allen of the Transmission Development Group and J. Lucas and C. Matusovich of the Materials Section.

TABLE OF CONTENTS

Page

LIST OF ILLUSTRATIONS

LIST OF TABLES

<u>LIST OF SYMBOLS</u>

C	carbon
Cr	chromium
E_s	estimated mean endurance strength at an infinite number of cycles
E_t	sample endurance strength at an infinite number of cycles
$\overline{E}_t$	arithmetic mean of E_t
F	facewidth of gear, in.
Fb	bending stress in gear, psi
Fe	Iron
J	gear geometry factor
Km	load distribution factor
Ko	overload factor
Ks	size factor
Kv	dynamic factor
Mn	manganese
Mo	molybdenum
N	number of cycles
n	number of test points
Ni	nickel
Pd	diametral pitch of gear
Pm	maximum test load in curve shape equation
R_c	Rockwell case hardness
S	standard deviation

Si	silicon
x	fatigue strength at given number of cycles
$\bar{X}$	mean load, lb
$S/\bar{X}$	coefficient of variation, %
W_t	tangential tooth load, lb
α	evaluated constant in curve shape equation
β	evaluated constant in curve shape equation = α/E_s
γ	evaluated constant in curve shape equation
O	indicates fractured specimen
O→	indicates runout (specimen did not crack)

INTRODUCTION

Increasing demands are being placed on the power transmission designer to improve constantly the power-to-weight ratio and reliability of drive train components. This is especially true in helicopter, V/STOL, and many other aircraft applications. These requirements necessitate an increasing use of higher strength as well as lighter weight materials.

Recent manufacturing and processing developments have introduced precision forging techniques that minimize the initial machining operations and lower material and manufacturing costs. In addition, higher mechanical properties result from better control of grain size and orientation (grain flow). Several programs to determine the bending fatigue properties of case-hardened gears produced by conventional and high energy forging techniques have been conducted in recent years. In one of these programs (Reference 1), High Energy Rate Forged (HERF) gears with integrally forged gear teeth and gears conventionally cut and ground from pancake forgings were tested. Test results indicated that the HERF gears had improved fatigue strength as compared to the more conventionally produced gears.

This report presents the results of a program conducted by Sikorsky Aircraft to evaluate the comparative fatigue strength of three advanced (high energy) forging processes producing gears with integrally forged teeth and gears fabricated from conventional pancake forgings. The three advanced processes include the use of two pneumatic-mechanical press systems and one mechanical press system.

FORGING MANUFACTURE

RAW MATERIAL

Inasmuch as the goal of the program was to evaluate the relative static and bending fatigue strengths of aircraft quality spur gears manufactured from forgings produced from conventional and high energy forging methods, it was desirous to minimize material, manufacturing, and testing variables. For this reason, a common heat of steel was procured.

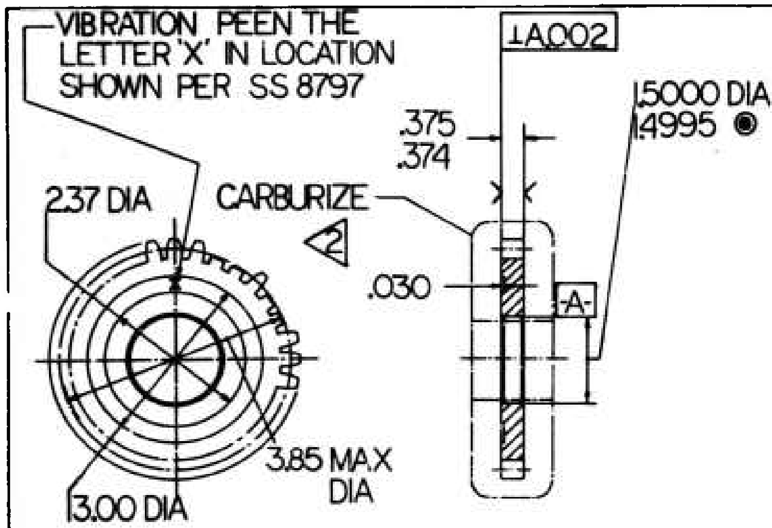
The material selected was AMS 6265, an SAE 9310 vacuum-melt carburizing steel widely used for helicopter and fixed-wing aircraft gearing. A total of 48 feet of 2-1/8-inch-diameter bar stock of a common heat was procured. The material was received at Sikorsky Aircraft as 12-foot bars with proper documentation to certify that all bars were from the same heat. The material was checked, and of the total quantity, approximately 8 feet was supplied to each of 6 forging manufacturers.

DIE DESIGN

Prior to fabricating the dies for the advanced forgings, a review of forging techniques and tolerances was made. Comments were solicited from each forging manufacturer and the gear manufacturer selected to participate in the program. To reduce the number of machining operations from initial forging to the finished gear stage, it was considered desirable to fabricate the forgings so that only a minimum amount of stock removal was necessary. The more important areas for maintaining a uniform flow pattern were on the tooth roots and flanks. In addition, assurance was sought from each of the forging manufacturers producing the advanced gear forgings that his forging technique (i.e., billet size, number of blows, amount and location of flash, etc.) would produce the best grainflow (i.e., parallel to the tooth profile) in his finished gears.

On the basis of this review, each forging manufacturer was instructed to produce blanks with a tooth profile within .010 to .014 inch of the finished involute profile as defined by the detail gear drawing, Figure 1. The .010- to .014-inch tolerance was considered a practical forging tolerance and was considered the necessary stock to accommodate heat-treat distortion and the necessary machining operations. Table I outlines these requirements.

On the basis of past forging experience, each of the forging manufacturers felt that his proposed forging design would produce the best grain flow in the finished gears. It is interesting to note that all three forgings were different in configuration.



NOTES

1. DIAMETERS MARKED ◉ TO BE CONCENTRIC TO EACH OTHER WITHIN .002 T.I.R.
2. CARBURIZE GEAR ALL OVER PER SS8015 TO PRODUCE .035 TO .045 DEPTH OF CASE IN FINISHED PART. BEFORE FINISH MACHINING HEAT TREAT TO ROCKWELL C58–64 OR EQUIVALENT CASE HARDNESS WITH RC 34–40 CORE HARDNESS.
3. SURFACES MARKED √ TO HAVE 32√ EXCEPT AS NOTED SS5100 SHALL APPLY FOR HOLES UNLESS OTHERWISE INDICATED. AREAS OF TRANSITION SHALL CONFORM TO THAT SPECIFIED FOR THE ROUGHEST ADJACENT FINISHED AREA UNLESS OTHERWISE INDICATED.

SPUR GEAR DATA

NO. OF TEETH 32
DIAMETRAL PITCH 8
PRESSURE ANGLE 22½°
PITCH DIAMETER 4.000
BASE CIRCLE DIAMETER 3.6955
OUTSIDE DIAMETER 4.2500 / 4.2450
ROOT DIAMETER 3.6934 / 3.6924
CHORDAL TOOTH THICKNESS .1943 / .1935
CHORDAL ADDENDUM .12735
MAX INVOLUTE PROFILE ERROR AT T.I.F. + .0003
– .0003 AT TIP + .0000 / – .0006
FULL FILLET RADIUS .0625

Figure 1. Test Gear Single Tooth Fatigue Test.

FORGINGS

Other than the requirements for grain flow, gear tooth dimension and tolerance, and as-forged gear blank size, the forging procedures to be used by each manufacturer were established by the individual forging company to accommodate his equipment, experience, etc. Billet size, upset ratio, number of forging operations, heating procedures, and temperatures were determined and applied by the forging manufacturers.

TABLE I. GEAR GRINDING AND PROCESSING ALLOWANCES

Operation	Allowance (per side)
Green Grinding	.003 inch
Heat-Treat Distortion	.005 inch
Eccentricity (base circle and O.D. to pitch diameter)	.002 inch
	.010 inch min. total

PANCAKE FORGINGS

The conventional pancake forging blanks, shown in Figure 2, were forged by a steam hammer in several blows at an initial forging temperature of 2200°F. After forming, the blanks were process annealed at 1200°F for one hour. They were then air-cooled, producing a Brinell hardness of 197.

ADVANCED FORGINGS

Process "A"

The process "A" forging source used a die design that formed most of the flash material into a flange as shown in Figure 3. The procedures used by this source consisted of an initial billet upset following an atmospheric heating to 1850°F. After air cooling, the intermediate billet was grit-blasted, and the outside diameter machined to 3,780 inches. The forging company has indicated that the purpose of the machining operation was to remove scale and to decarbonize. The final forging operation, from intermediate billet to final gear blank, was preceded by a heat soak of 1750°F. The flash configuration is obtained by using a large-diameter flat striker and more material

Figure 2. Conventional Pancake Forging.

than actually required. The flash was removed prior to shipment to Sikorsky Aircraft.

Although the tooth profiles and spacing were generally good, minor nicks on flat spots appeared on random teeth and are visible in Figure 3, bottom view. The cause of these problem areas are unknown at this time, and, although they did not affect the test, it would be necessary to rectify this problem before the gears could be used in an aircraft transmission system.

Process "B"

Of the three advanced processes evaluated, only the manufacturer of process "B" obtained a final gear blank with one forging hit. This manufacturer preceded the operation by heating the billets in an inert atmosphere to 2100°F. The flash configuration formed, as shown in Figure 4, was accomplished by using a ram of diameter smaller than the gear base circle. Excess metal flowed around the ram and axially along the female teeth of the die to form a lip on one side of the gear blank, as shown in the top view of Figure 4. The indented ring visible in the bottom view was formed by the extractor during removal of the blank from the die.

Process "C"

The gear blanks manufactured by process "C" have the least amount of flash, when compared to the other forgings. The top and bottom of the blanks are nearly identical with only a light extractor impression on one side, as seen in Figure 5. The flash configuration indicates that the initial billet volume was closely controlled in this process; the flow of material was uniform in both directions along the gear tooth flanks. The die striker and reactor fit into the internally splined gear die with approximately .030 to .050 inch clearance between all tooth surfaces. The resultant flash formed a thin shell along the outside contour of the gear teeth on both top and bottom of the blank.

The process "C" forging was produced by immediately successive forging hits after an initial heat soak brought the billets to 1850°F. The intermediate billet size was approximately 3.6 inches in diameter and .95 inch thick. The energy transferred to the billet during initial forging operation maintained the billet temperature at approximately 1850°F for the second forging operation.

All the gear blanks received by Sikorsky conformed to the requirements of Table I. The final as-forged gear blanks are shown in

Figures 3 through 5. It can be seen by the flash obtained that each forging source used a different die design. Table II outlines the pertinent forging data. It is noteworthy that a considerable number of procedural differences existed among the three forging processes. Not only did the die designs differ, but the basic metal working concepts varied from source to source. The number of forging operations, heating procedures, and forging machines all differed; but each process produced acceptable gear blanks, and none presented any unusual problems in establishing the rough machining and blanking procedures (although some machining was required to shadowgraph-inspect the individual blanks for tooth form, due to the flash overrun into the tooth profiles).

GEAR MANUFACTURE

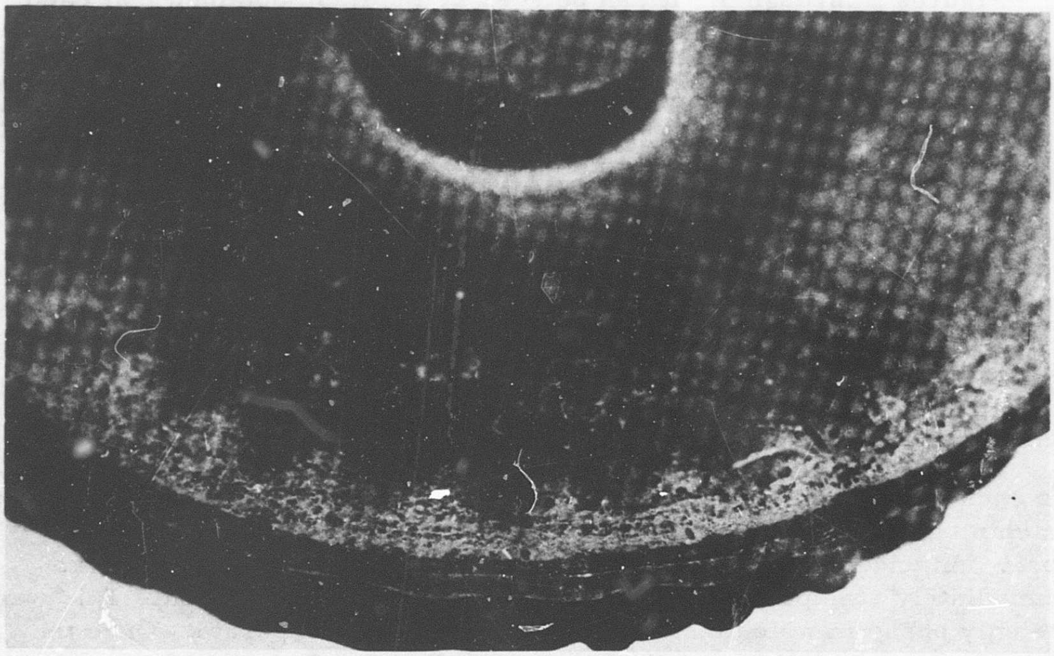
As each gear blank lot arrived, it was identified and serialized. The first machining phase consisted of rough machining both faces and the gear bore. An undercut was made on one face, and the serial number was immediately stamped in this area for permanent identification. This was the only phase in which the four sources were kept separate. Once the groove was established and the blank serialized, it became impossible to lose identity of the gears during either processing or testing. The pancake forgings were then hobbed to the tooth dimensions of the advanced forging blank, i.e., within .010 to .014 inch of the final gear profile.

All gears were then intermixed in a systematically arranged sequence for green grinding. During the green-grinding operation, difficulty was experienced in maintaining proper contour of the grinding wheel. Sample as-forged gears were examined on a Fellows involute checker, and Figures 6 through 8 show the actual deviations from true involute form. When compared to the as-hobbed involute form, in Figure 9, it is obvious that additional die development is necessary to provide a gear blank that can be heat-treated and finish-ground without prior green grinding or hobbing.

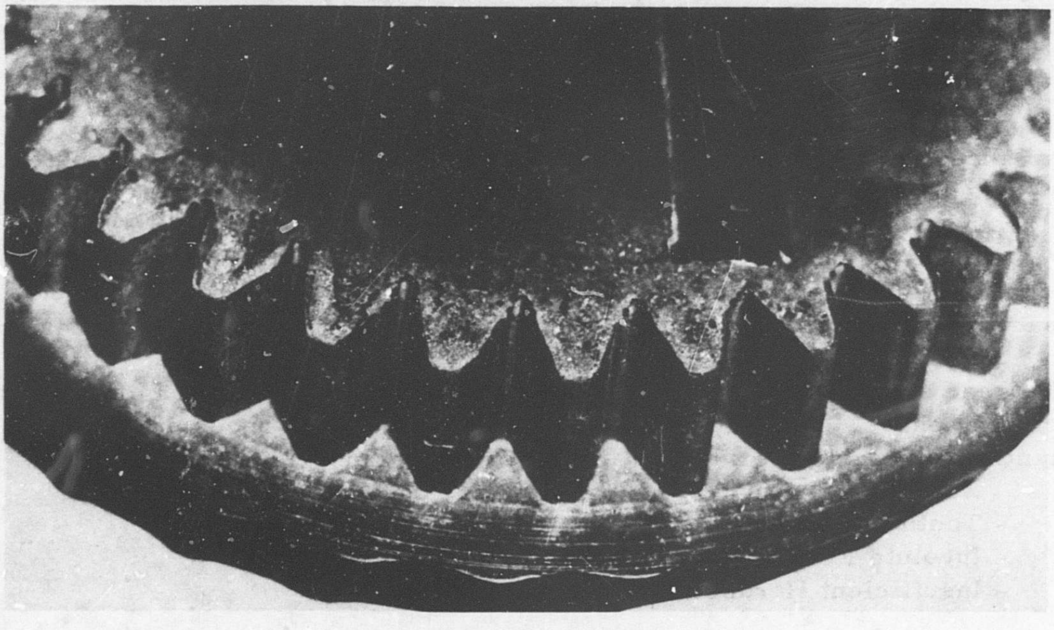
The gear shop reported that considerable time was consumed in the green-grinding phase. The key problems contributing to the necessity of constantly redressing the wheel were, in order of importance:

- Tooth-Spacing Errors
- Involute Form Errors
- Insufficient Hardness

The gear shop also noted a preference toward subjecting all the forgings to a preliminary drawing operation in order to obtain a hardness of R_c 30 minimum. All gears were received with a hardness ranging from R_c 21 to R_c 28; however, a drawing operation was eliminated from the processing

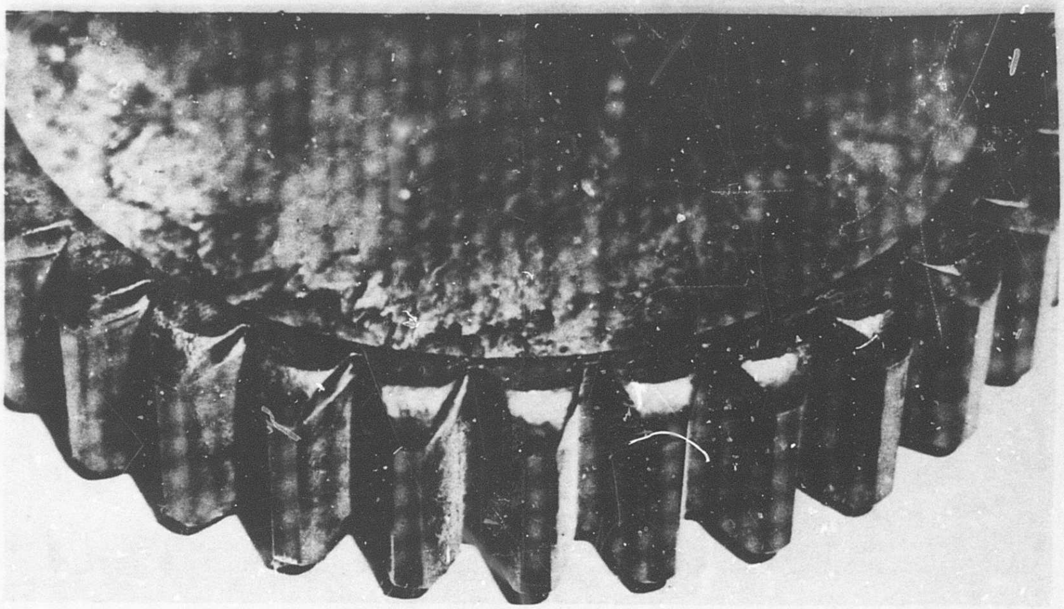


TOP VIEW

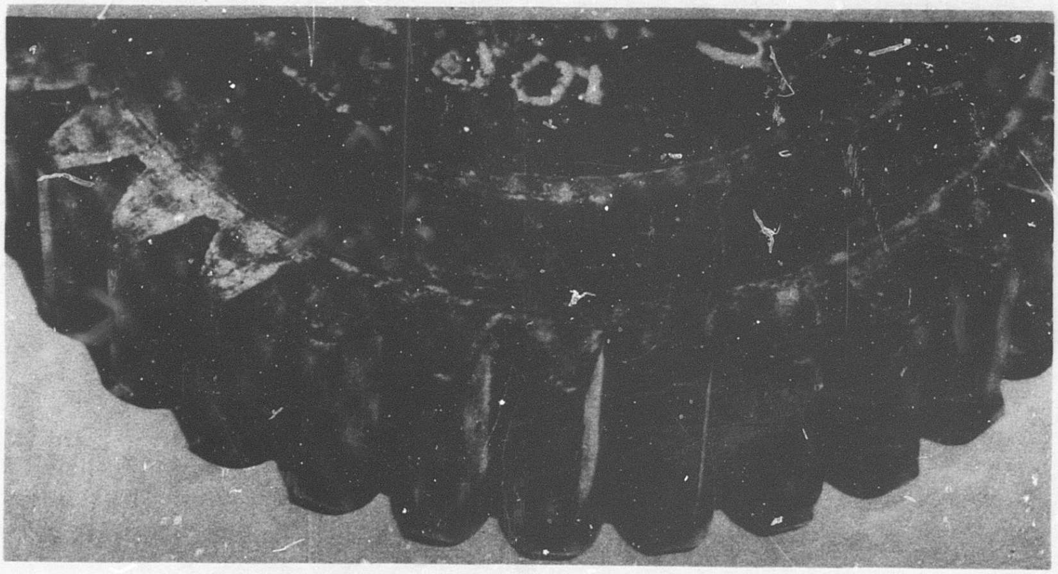


BOTTOM VIEW

Figure 3. Process "A" As-Forged Blank.



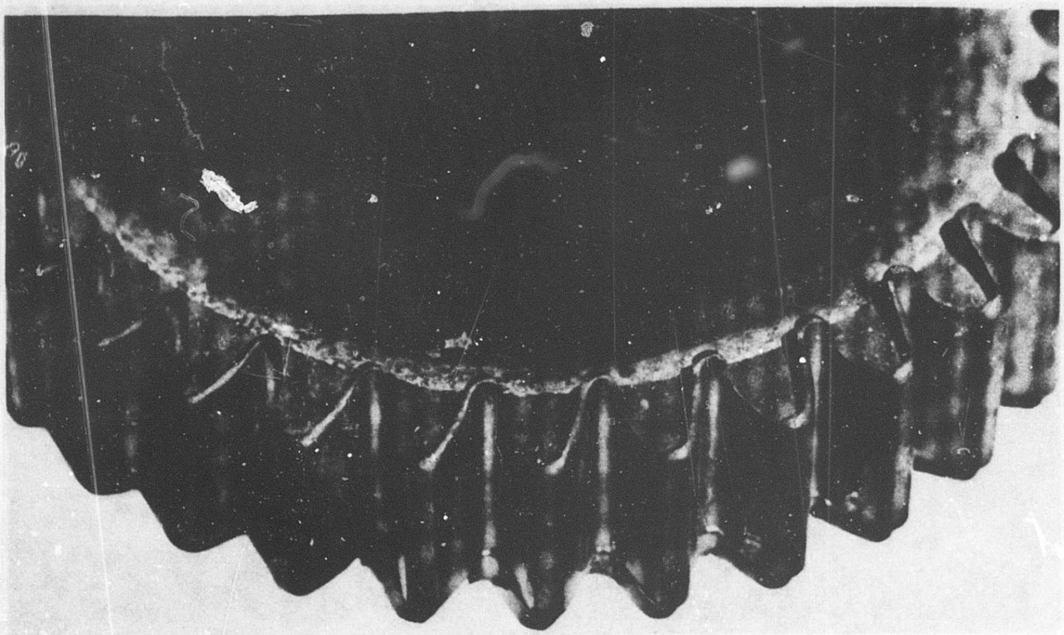
TOP VIEW



BOTTOM VIEW

Figure 4. Process "B" As-Forged Blank.

TOP VIEW



BOTTOM VIEW

Figure 5. Process "C" As-Forged Blank.

TABLE II. BASIC FORGING DATA

	Process			
	"A"	"B"	"C"	Conventional
Initial Billet Size, in.	2-1/2 dia. x 1.81	2-1/2 dia. x 1.42	2.125 dia. x 2.50	2.50 dia. x 2.50
Number Forging Hits	3*	1	2	-
Forging Temperature First Hit, °F	1,850	2,100	1,850	2,200
Intermediate Billet Size, in.	-	none	3.6 dia. x .95	none
Intermediate Processing	Grit Blast and turn to 3.780-in. Diameter	-	none	-
Forging Temperature, °F	1,775	-	1,850	-
Forging Press	Pneumatic-Mechanical	Pneumatic-Mechanical	Mechanical	Steam Hammer

*Intermediate Billet Produced by Two Blows

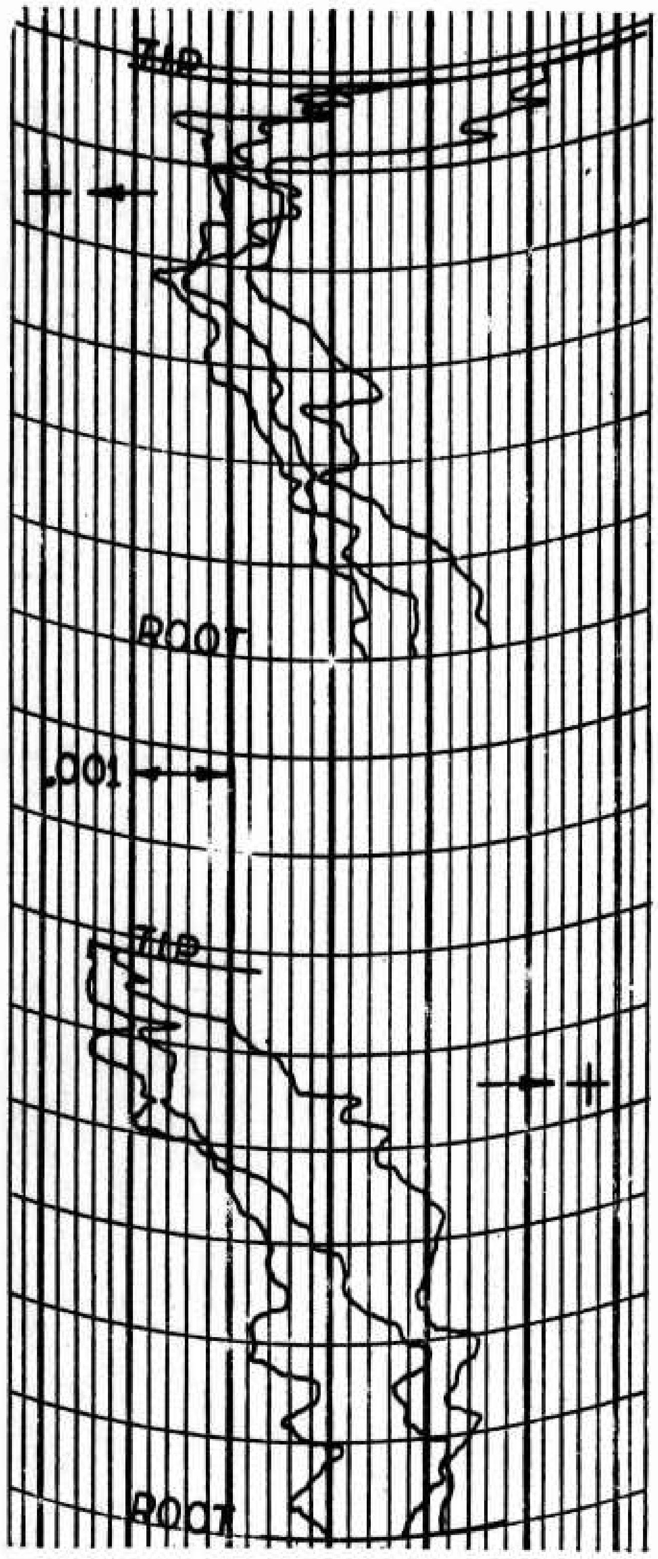


Figure 6. Involute Profile Chart, Process "A" As-Forged Test Gear, S/N 10.

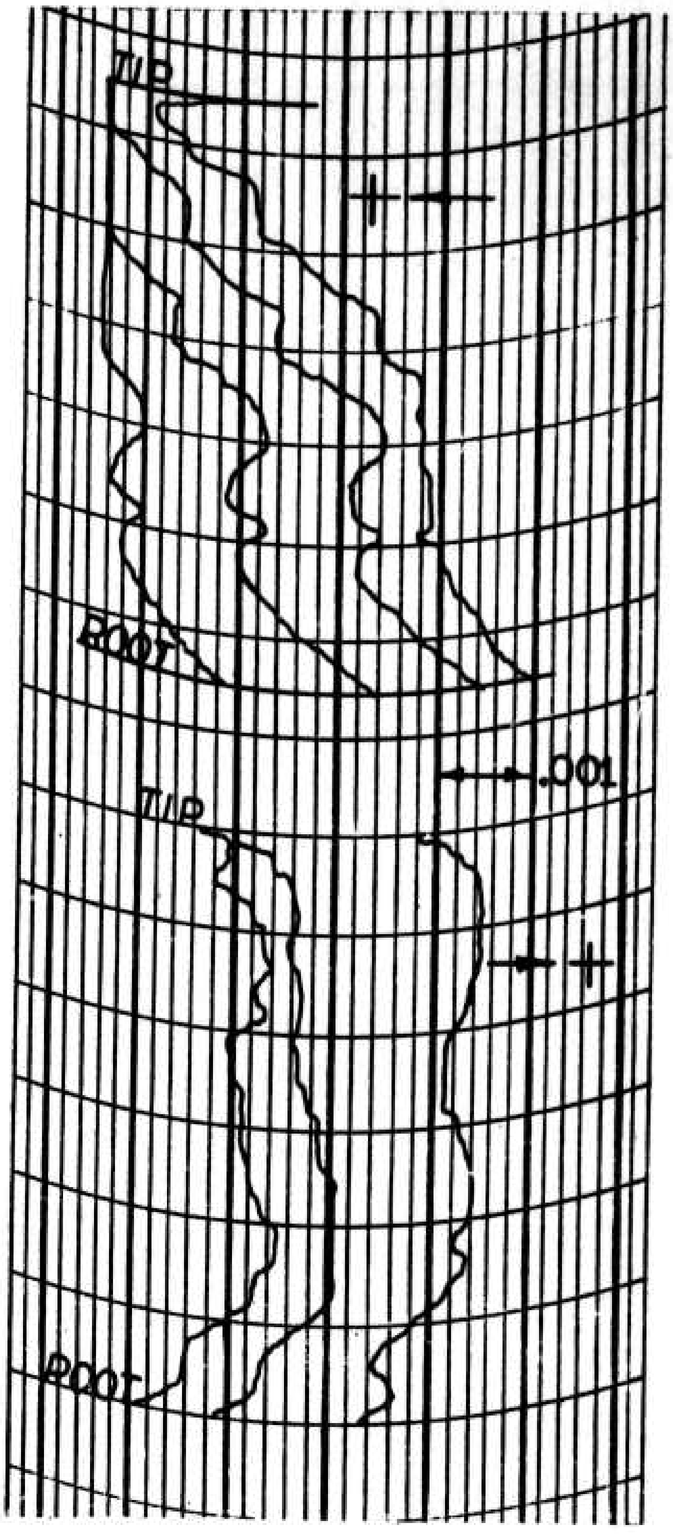


Figure 7. Involute Profile Chart, Process "B" As-Forged Test Gear, S/N 20.

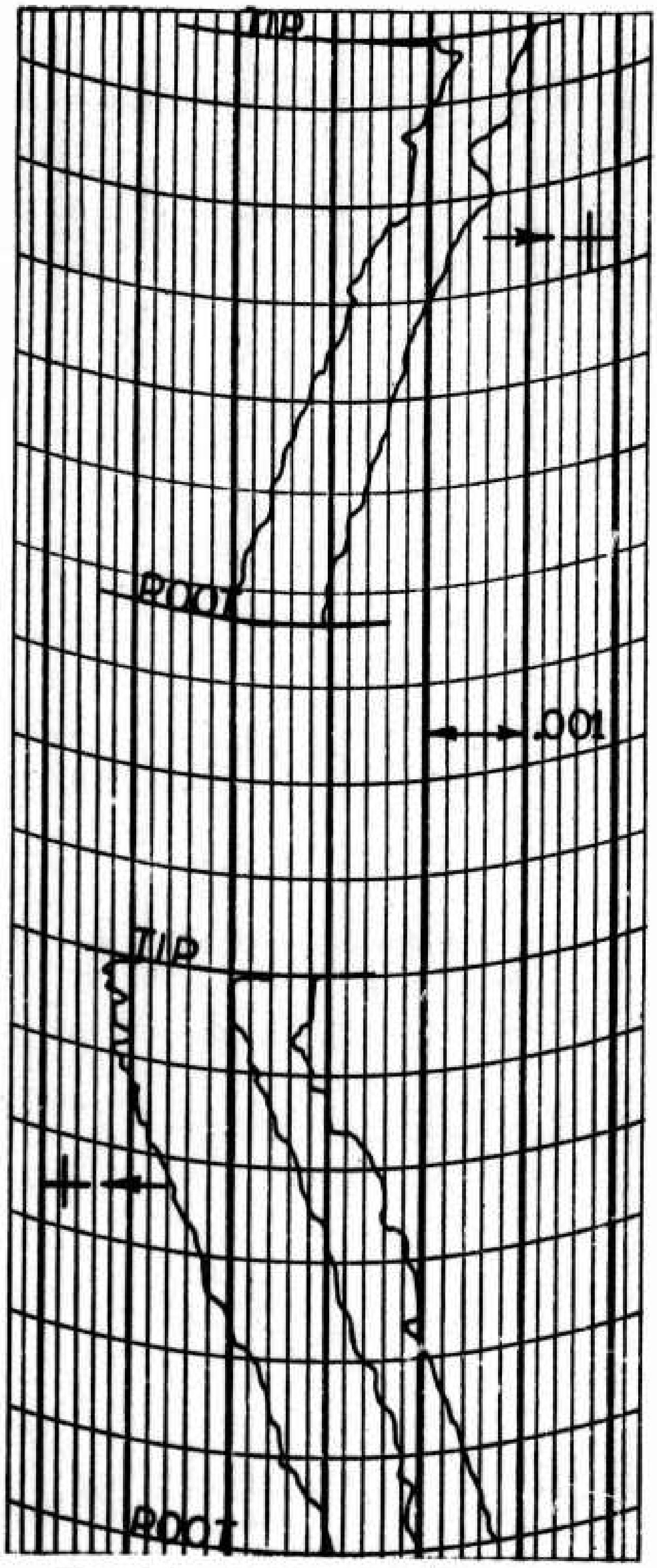


Figure 8. Involute Profile Chart, Process "C" As-Forged Test Gear, S/N 30.

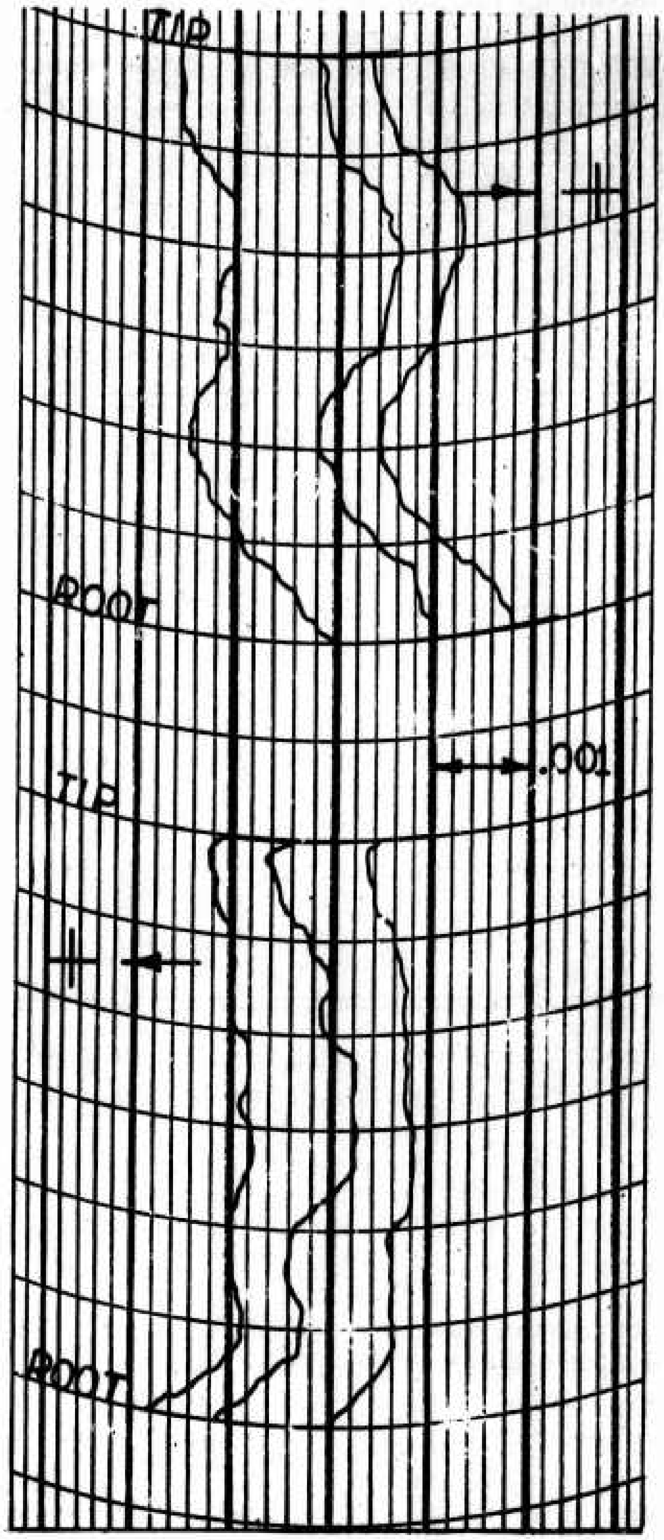


Figure 9. Involute Profile Chart, Conventional As-Hobbed Test Gear, S/N 40.

because all three advanced forging sources felt that an additional drawing operation might be detrimental to grain size and orientation. The softness of the forgings tended to load up the grinding wheel, thus requiring constant redressing, a situation not acceptable for production quantities of gears.

Inspection following green grinding showed that all three advanced forging gear samples failed to clean up completely. Green-grinding discrepancies are listed in Table III.

TABLE III. GREEN-GRINDING DISCREPANCIES

Process	Problem Area
"A"	The O.D. of better than 50 percent of the teeth did not clean up. Additionally, random small areas approximately 45° from the base of the root did not clean.
"B"	The flanks of random teeth did not clean completely, indicating tooth-spacing errors.
"C"	Random small areas 45° from the base of the root did not clean on these gears.
Conventional	All tooth surfaces cleaned up.

All of the preceding problems might have been minimized had the program funding and schedule permitted several iterations in die design and development.

Upon completion of green grinding, all test gears were carburized and heat-treated as a single lot to produce a .035- to .045-inch case depth and a core hardness of R_c 34 to R_c 45.

The final grinding operation was accomplished on a Detroit gear grinder using an 8-inch wheel diameter. The gears were again systematically randomized in a new sequence and ground on a common machine as shown in Figure 10. Gear profile cleanup during final grinding was good except that the tips of some teeth of gears produced from process "A" had areas that did not clean up. Since this area was outboard of the point of loading and would not influence the test results, the gears were considered to be acceptable for testing.

After grinding, 16 of the 32 teeth were removed as shown in Figure 11. This was done to facilitate assembly in the test fixture.

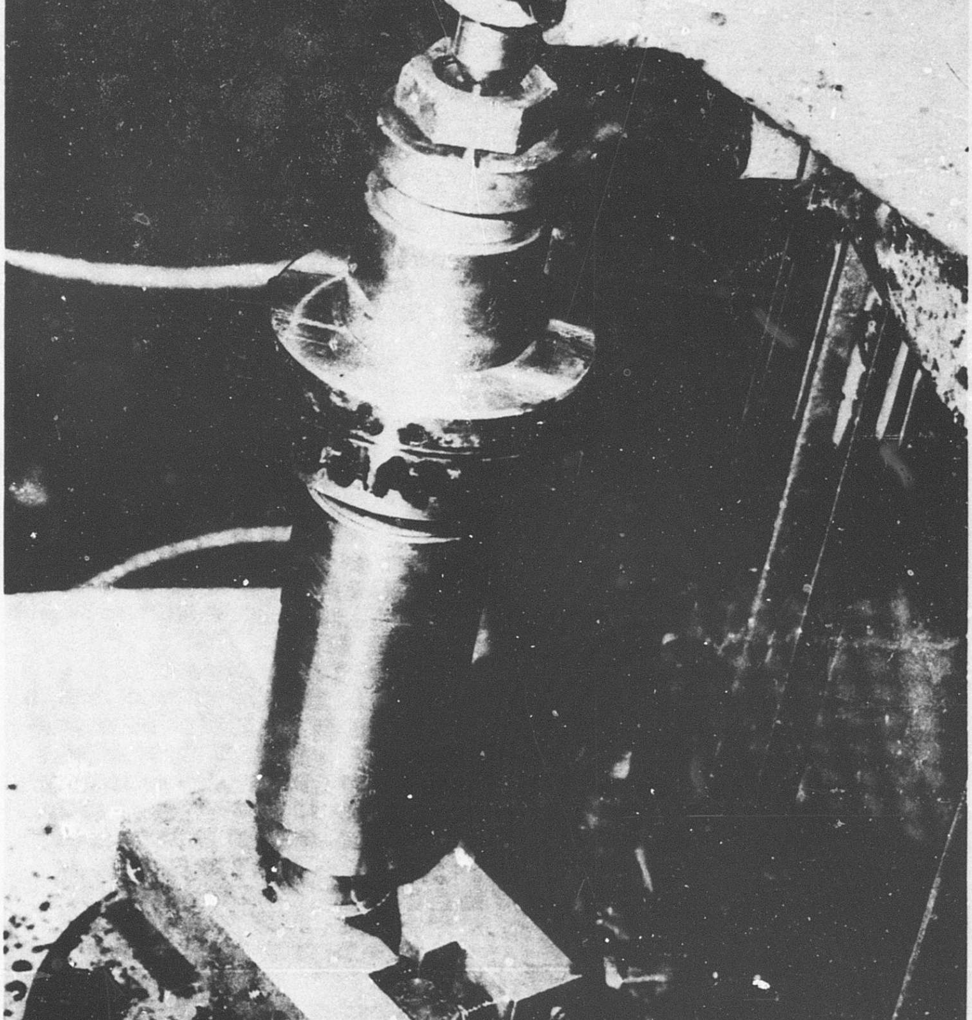


Figure 10. Detroit Gear Grinding Setup.

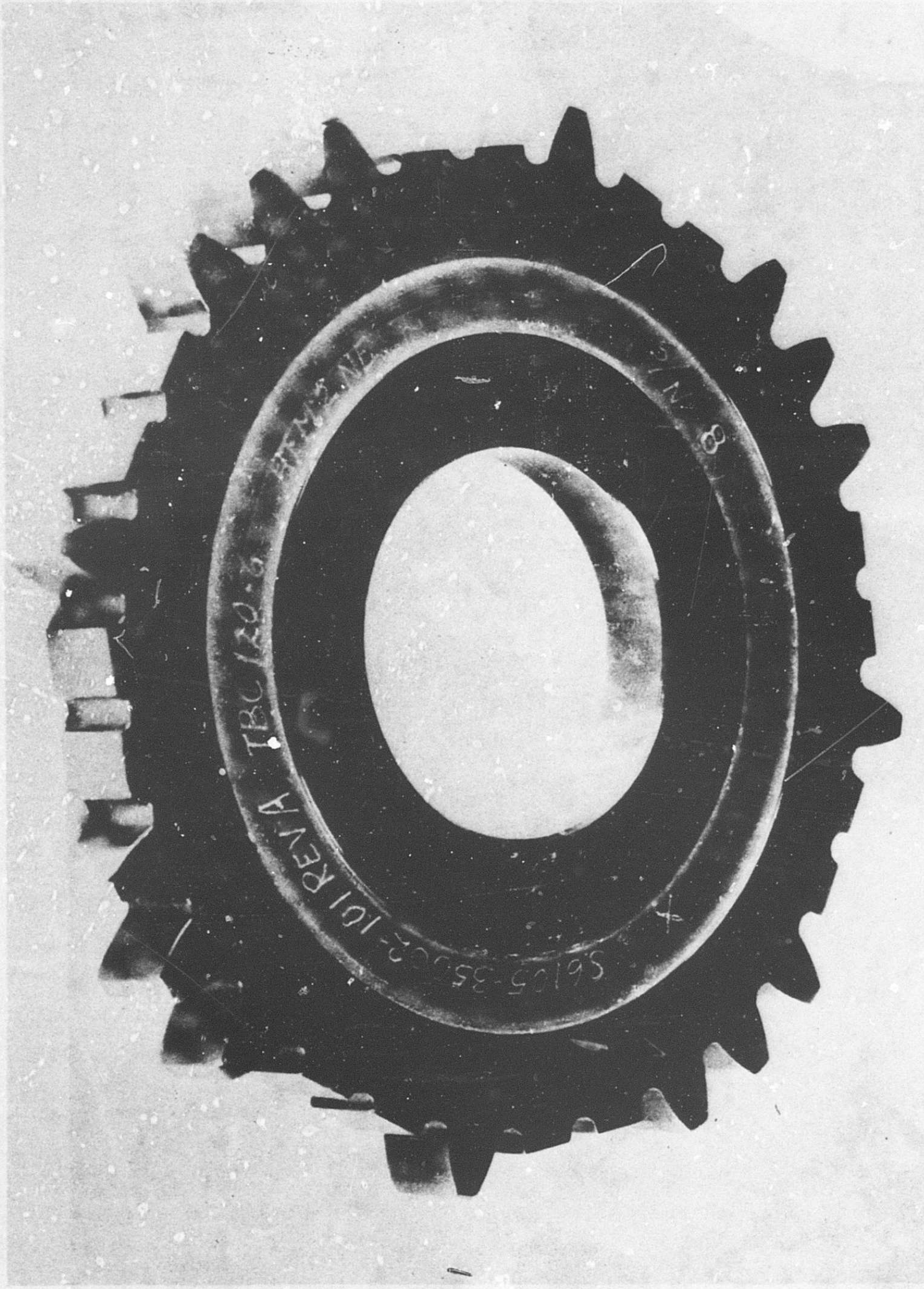


Figure 11. Finished Test Gear.

TEST PROCEDURE

FATIGUE TEST SETUP

The single tooth fatigue tests were conducted on a special test fixture designed and manufactured by Sikorsky Aircraft. In this test series, three of the fixtures were mounted in Sonntag Model SF-1-U universal fatigue testing machines fitted with five-to-one load amplifiers. Figures 12 and 13 illustrate the Sikorsky test fixture and Sonntag machines respectively. Figure 14 shows the complete test arrangement. The test or "Highest Point of Single Tooth Contact" load was applied by means of a loading pin which contacted the gear tooth normal to the involute profile at the "worst load position" (Reference 2). A tungsten carbide tip was brazed to the loading pin to improve the durability of the surface contacting the gear tooth.

The normal tooth load was reacted by a reaction tooth which contacted a contoured support block. The contact was over the entire tooth profile to reduce the stress and to prevent the reaction tooth from failing. The test fixture was designed in such a manner that the loading pin automatically contacted the test tooth at the "worst load" point when the gear was installed in the fixture, and the reaction tooth was positioned to make contact with the reaction block. Figures 15 and 16 show respectively the point of contact and direction on the gear tooth profile for the "worst load" condition and a sketch of the test fixture. A preload was maintained on the test tooth when the gear was tightened in the fixture to prevent separation of the reaction tooth and reaction block which could cause an error in the load application point.

Load cells were installed in series with the loading pin for static and dynamic load determination. Each load cell was calibrated statically in the Riehle PS-60 Tensile Machine at the beginning of the test and every two months thereafter while testing was in progress. An Ellis BA-12 budge amplifier and cathode ray oscilloscope were used to read the strain gage bridge output. The calibrated load cells were used as the primary load-measuring system for test setup and were used for checking the applied loads twice daily while a test was in progress.

Some difficulty was encountered in the preliminary fatigue tests due to cracking of the loading pin tooth contact surface. Cracking of the pin occurred primarily from impact loading at the moment that complete fracture of the test tooth occurred. To eliminate this problem, failure of the test tooth was considered to have occurred when a 1/16-inch crack was detected. A "microwire" or "failwire" technique was used for crack detection. Small-diameter copper wire was cemented to the sides of the

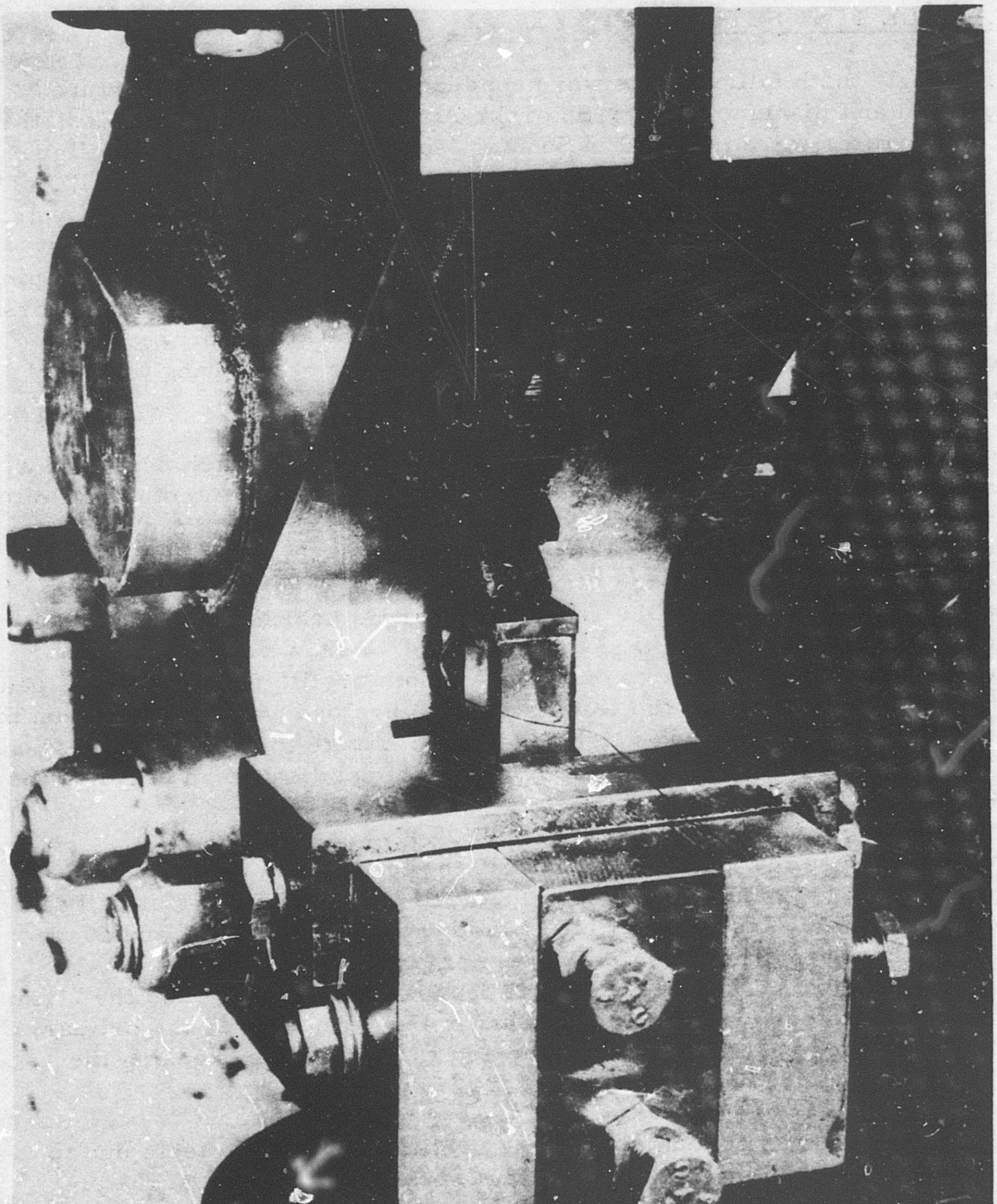


Figure 12. Sikorsky Aircraft Single Tooth Test Fixture.

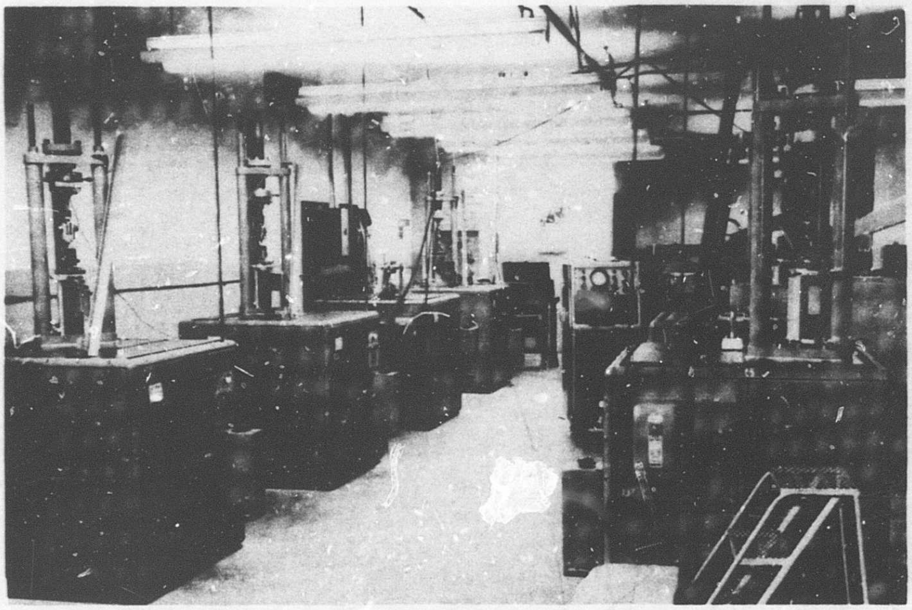


Figure 13. Sikorsky Aircraft Fatigue Test Laboratory.

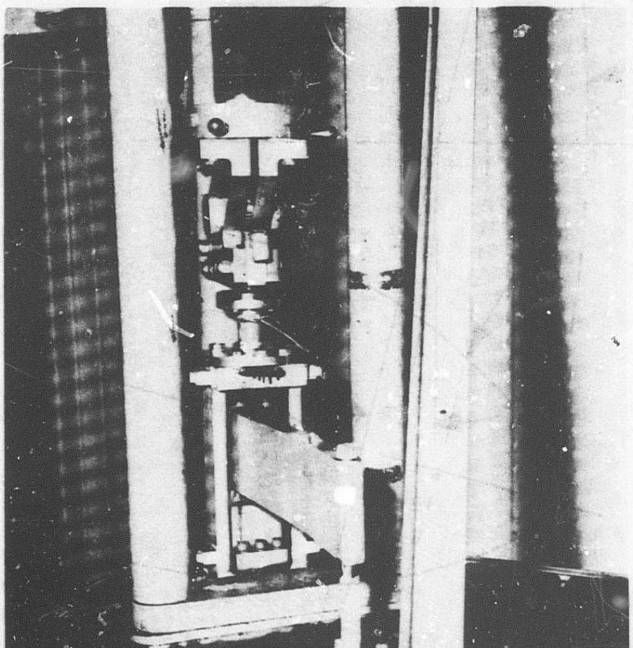


Figure 14. Fatigue Test Arrangement on Sonntag Machine.

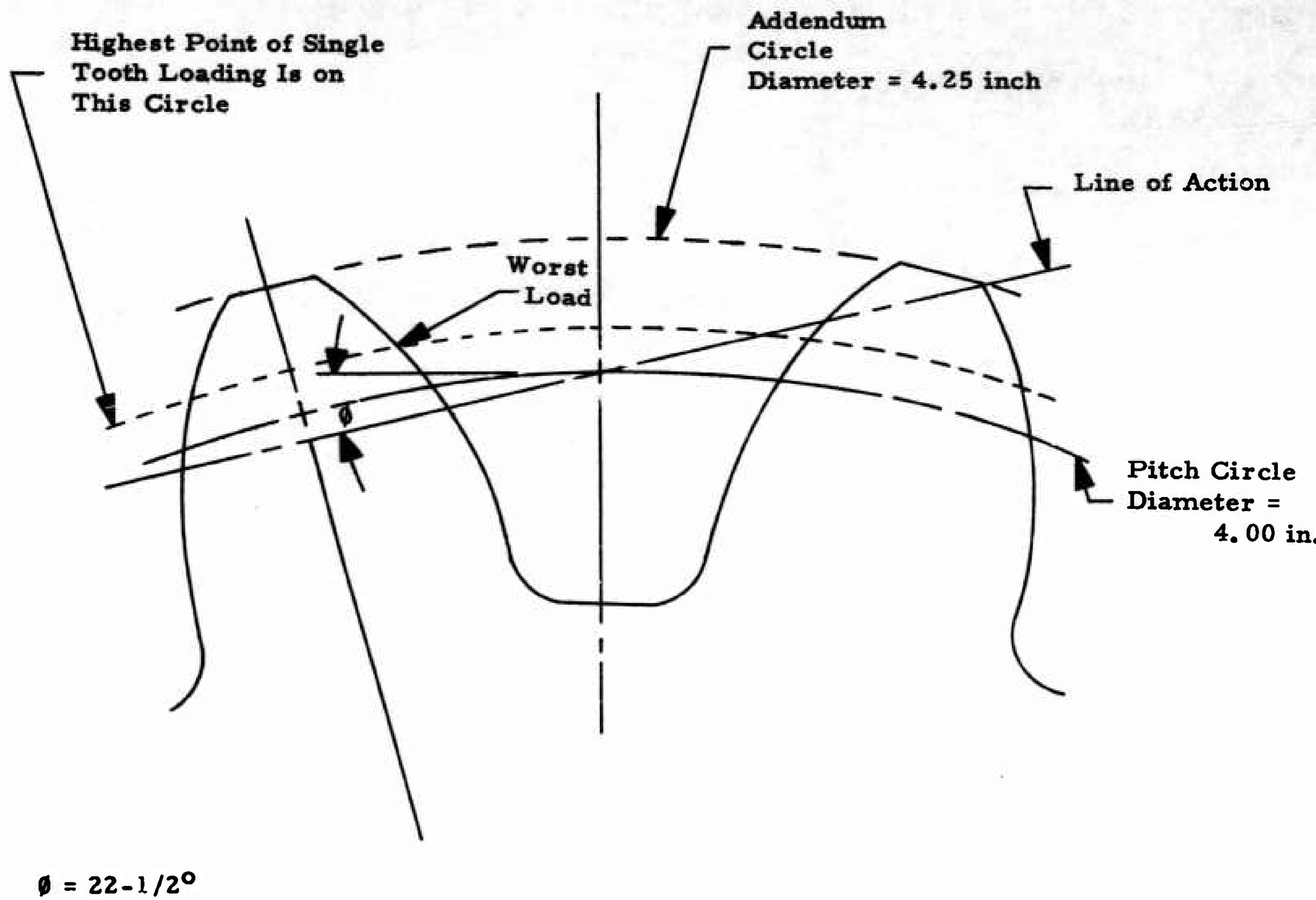


Figure 15. Schematic of Single Tooth Load Parameters.

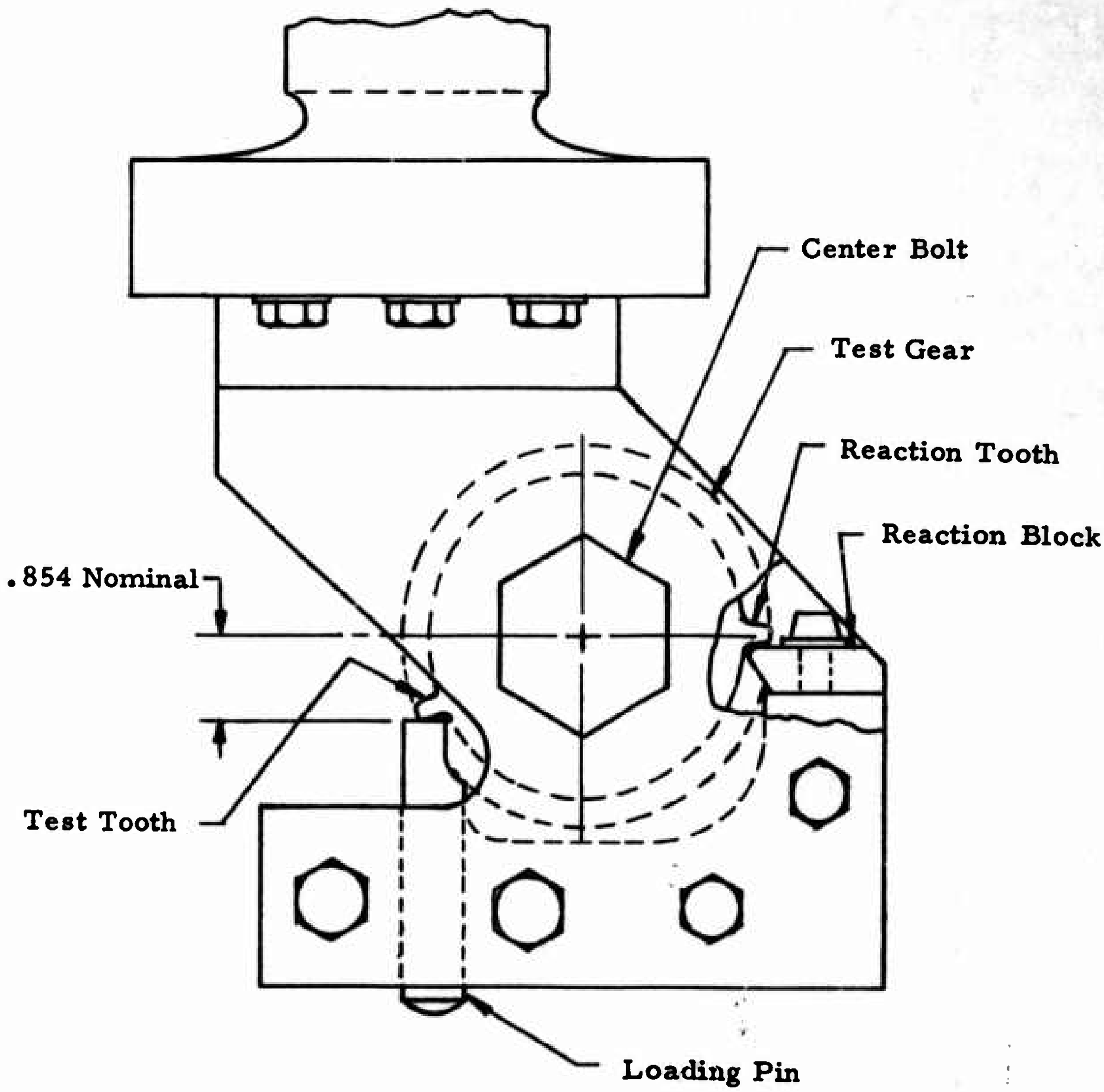


Figure 16. Schematic of Gear Test Fixture.

gear approximately 1/16 inch from the test tooth profile and was connected to the control system of the Sonntag machine. When a crack initiated in the test tooth and propagated under the wire (a 1/16-inch crack depth), the wire would break and the Sonntag machine would be shut off.

A total of 20 teeth were tested at a minimum of four load levels for each of the four forging processes. All test load levels varied sinusoidally from a 100-pound positive minimum load to whatever positive maximum load was required to obtain failures in the desired cycle ranges. This type of loading produced tooth bending in one direction only, which is typical of service pinions and gears. The positive minimum 100-pound load was maintained for all test load levels to prevent any impact loading which would occur if the minimum load was allowed to reach zero. All four test teeth of each gear were tested at a different load level. The test sequence was randomized with respect to forging process, test tooth, test load, and testing machine.

STATIC TEST

Single tooth static tests were conducted in the Riehle PS-60 Tensile Test Machine on the same gear configuration as previously discussed for fatigue tests. The same fixture used for the fatigue test was also used for the static tests. An adaptor was bolted to the top of the fixture to make an attachment possible in the upper head of the tensile machine. The lower head made contact with the load pin, which in turn applied load to the test gear. Figure 17 shows the fixture mounted in the tensile

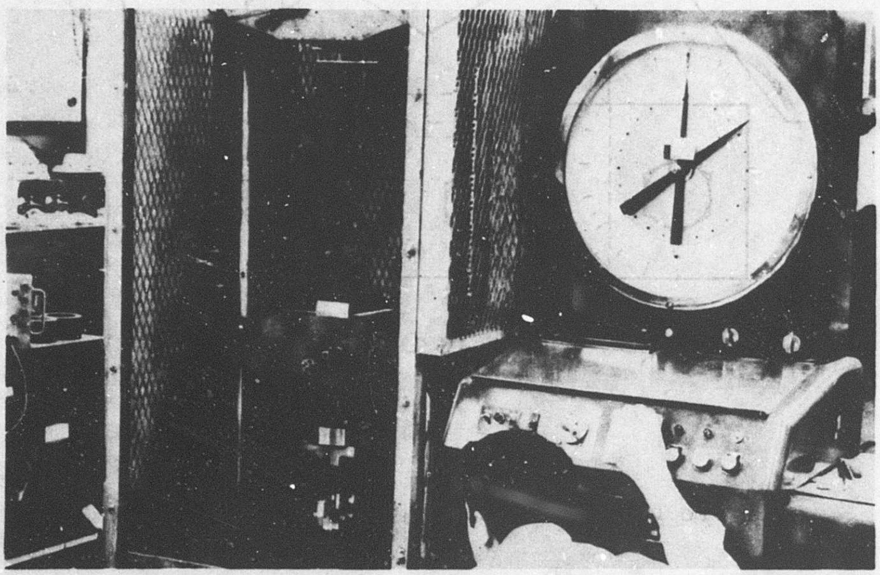


Figure 17. Static Test Arrangement in Riehle Tensile Test Machine.

machine. For the static tests, the loading point on the gear tooth was changed from the "worst load" condition to tooth tip loading. Figures 15 and 16 show respectively the point of contact and direction of the tip load on the tooth profile and a sketch of the test fixture with the dimensions used to obtain tip loading. This type of loading was determined to be necessary to prevent the loading point contact from rolling back into the root radius and off the edge of the loading pin because of the more ductile nature of the static fracturing. The ultimate load for each test tooth was read directly off the tensile machine dial.

TEST RESULTS

FATIGUE TEST

A summary of the fatigue test data is presented in Table IV. Figures 18 through 21 are plots of the data points and respective mean curves for each forging process. For comparative purposes, a composite of the four mean curves is presented in Figure 22. The mean fatigue strengths and standard deviations at 10^8 cycles, the coefficients of variation, and the constants of the curve shape equation for the mean curves are tabulated in Table V. The results in Table IV and Figure 22 show that the mean fatigue strength of the gears forged by processes "A", "B" and "C" are respectively 24 percent, 25 percent, and 44 percent higher at 10^8 cycles than the mean fatigue strength of the conventionally forged gears.

The results of the statistical analysis (Table VI) show that these observed increases in mean strengths at 10^8 cycles of the high energy forged gears over the conventional gears are statistically significant.

STATIC TEST

A summary of the static test data is presented in Table VII. The mean ultimate test loads, standard deviations, coefficients of variation, and results of a statistical analysis to determine if a significant difference existed between the ultimate mean strength of the conventional gears and the high energy forged gears are given in Table VIII. The results of the statistical tests show that although small differences exist between the means of the four forging processes, they are not significantly different based on a 90 percent confidence level.

Eight teeth were tested for each forging process. The testing sequence was randomized with respect to forging process, test gear, and test tooth.

The arithmetic mean, standard deviation, and coefficient of variation were determined for the ultimate loads for each forging process. A single-tailed "t" test was performed to determine if a significant difference existed between the mean of the conventional gears and either of the high energy forged gears.

TABLE IV. TEST DATA, SINGLE TOOTH FATIGUE TEST					
Forging Process	Serial No.	Tooth No.	Maximum Test Load (lb)	Cycles to Crack Detection x 10^6	Comments
"A"	03	A	3100	.0931	
		B	2700	.5566	
		C	3900	.0316	
		D	2300	20.0	No Fracture
	04	A	5500	.0068	
		B	2700	17.753	No Fracture
		C	3900	.0664	
		D	3100	.150	
	06	A	3900	.025	
		B	3100	.293	
		C	2700	20.0	No Fracture
		D	5500	.0049	
	07	A	2700	.573	
		B	3900	.0222	
		C	3100	.0893	
		D	5500	.0062	
	09	A	5500	.0073	
		B	3500	.2734	
		C	3100	20.0	No Fracture
		D	2700	20.0	No Fracture
"B"	12	A	3900	.0218	
		B	2300	10.764	
		C	3100	.0474	
		D	2700	.3164	
	13	A	5500	.0097	
		B	2300	20.0	No Fracture
		C	3100	.2276	
		D	3900	.1236	

TABLE IV - continued

Forging Process	Serial No.	Tooth No.	Maximum Test Load (lb)	Cycles to Crack Detection x 10^6	Comments
"B"	15	A	5500	.0077	
		B	2300	18.100	No Fracture
		C	3100	20.000	No Fracture
		D	3900	.102	
	16	A	3900	.093	
		B	3100	20.000	No Fracture
		C	5500	.008	
		D	2300	20.0	No Fracture
	20	A	5500	.0035	
		B	2300	20.0	No Fracture
		C	3100	.1094	
		D	3900	.0312	
"C"	23	A	3900	.817	
		B	4900	.0172	
		C	5500	.0086	
		D	3300	20.0	No Fracture
	24	A	5500	.0095	
		B	3300	16.108	No Fracture
		C	3100	20.0	No Fracture
		D			
	26	A	3500	.1314	
		B	3100	.148	
		C	3300	.2303	
		D	3900	.0831	
	27	A	3900	.039	
		B	5500	.008	
		C	3500	.090	
		D	3100	20.270	No Fracture
	28	A	3100	.0823	

TABLE IV - continued					
Forging Process	Serial No.	Tooth No.	Maximum Test Load (lb)	Cycles to Crack Detection x 10^6	Comments
"C"	29	A	3900	.070	
		B	5500	.0118	
		C	3300	1.1011	
		D	3100	20.0	No Fracture
Conventional	32	A	5500	.0046	
		B	3900	.0237	
		C	3100	.1282	
		D	1900	18.380	No Fracture
	33	A	3500	.0785	
		B	3900	.044	
		C	3100	.154	
		D	1900	17.900	No Fracture
	34	A	3500	4.544	
		B	3100	20.302	No Fracture
		C	2300	20.035	No Fracture
		D	5500	.0106	
	37	A	2300	.364	
		B	5500	.007	
		C	3900	.036	
		D	3100	.1022	
	38	A	4900	.0096	
		B	1900	20.0	No Fracture
		C	3100	.0831	
		D	2300	.441	

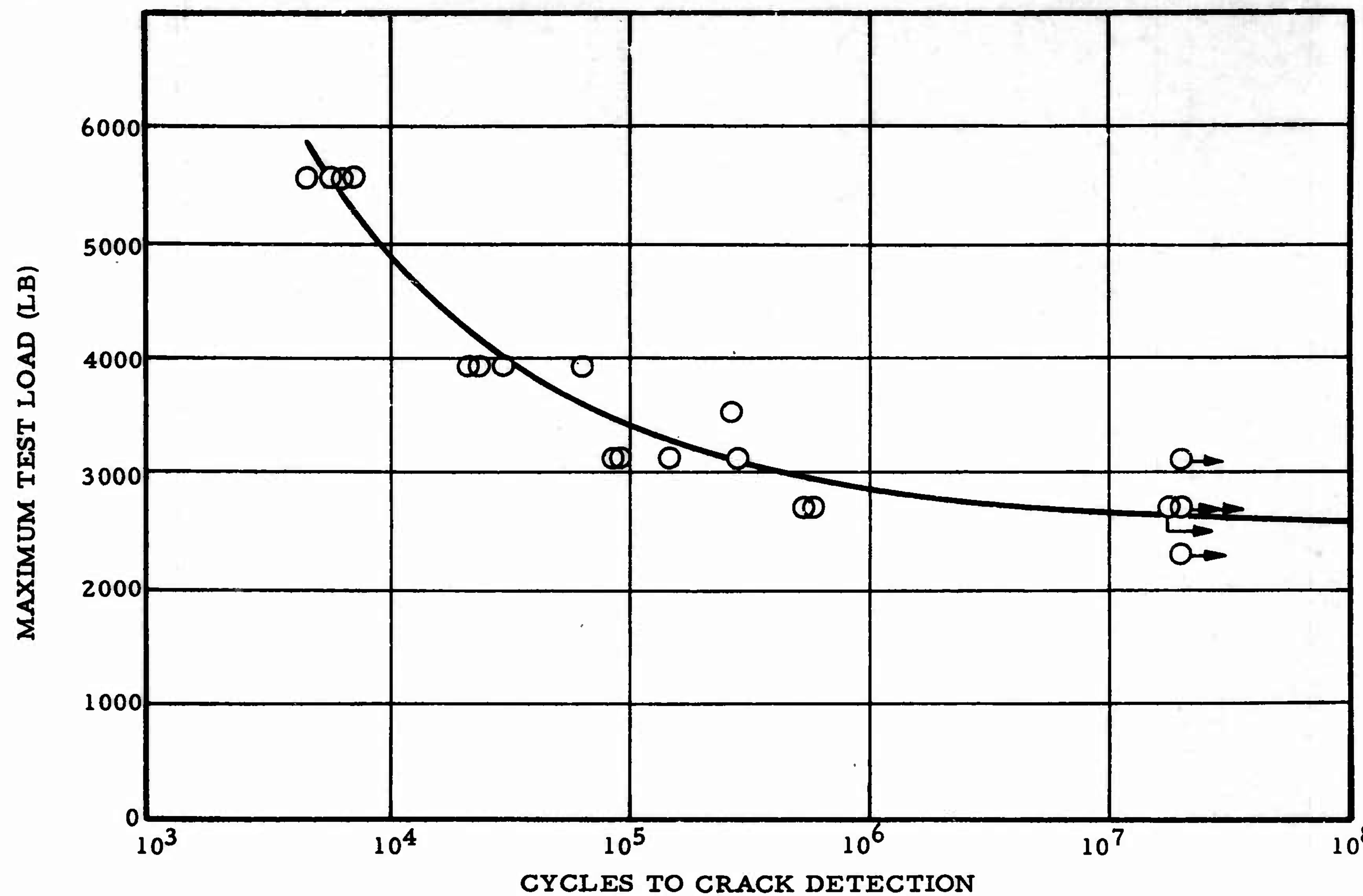


Figure 18. Single Tooth Fatigue Test Results for Gears Forged by Process "A".

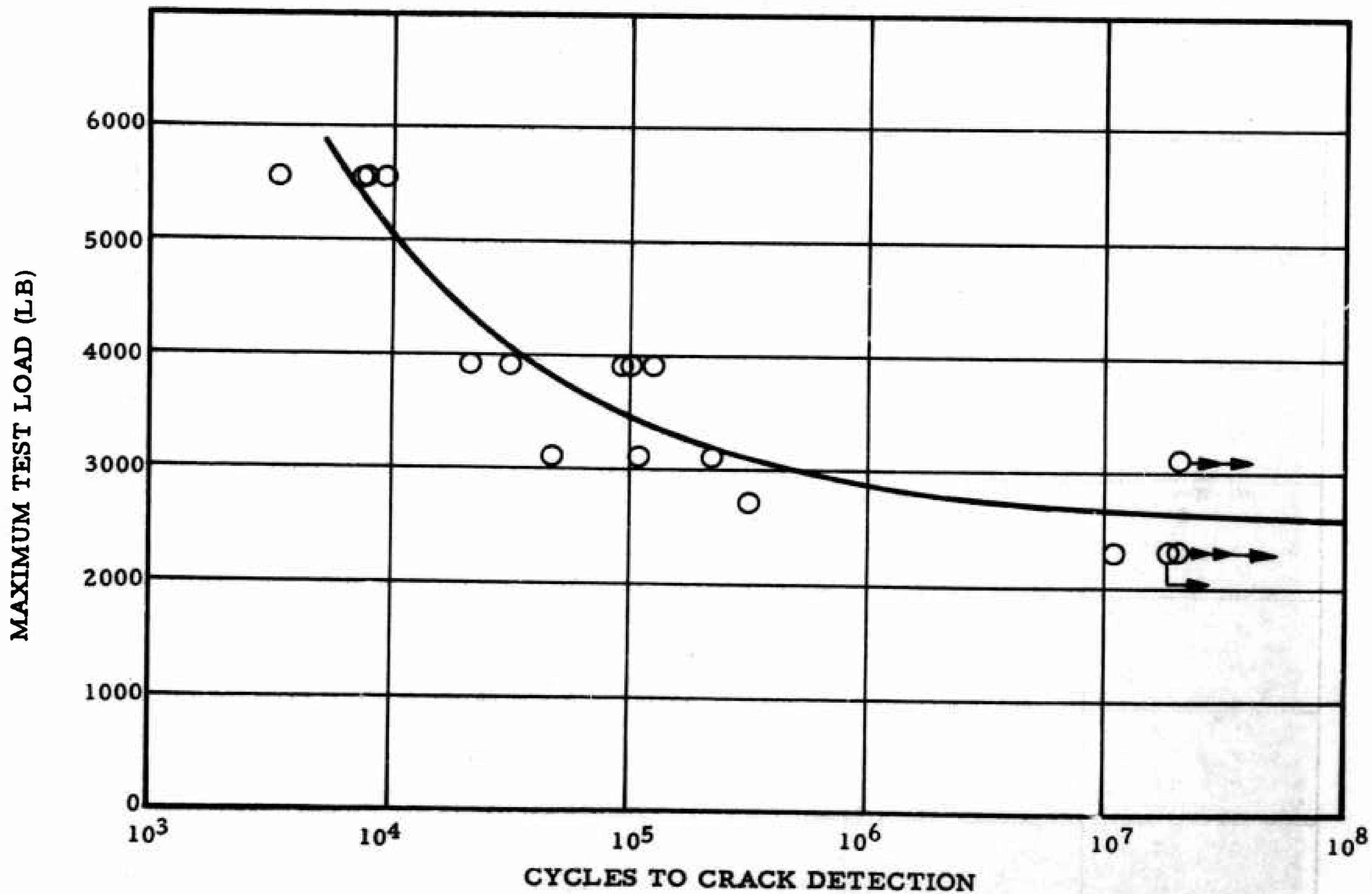


Figure 19. Single Tooth Fatigue Test Results for Gears Forged by Process "B".

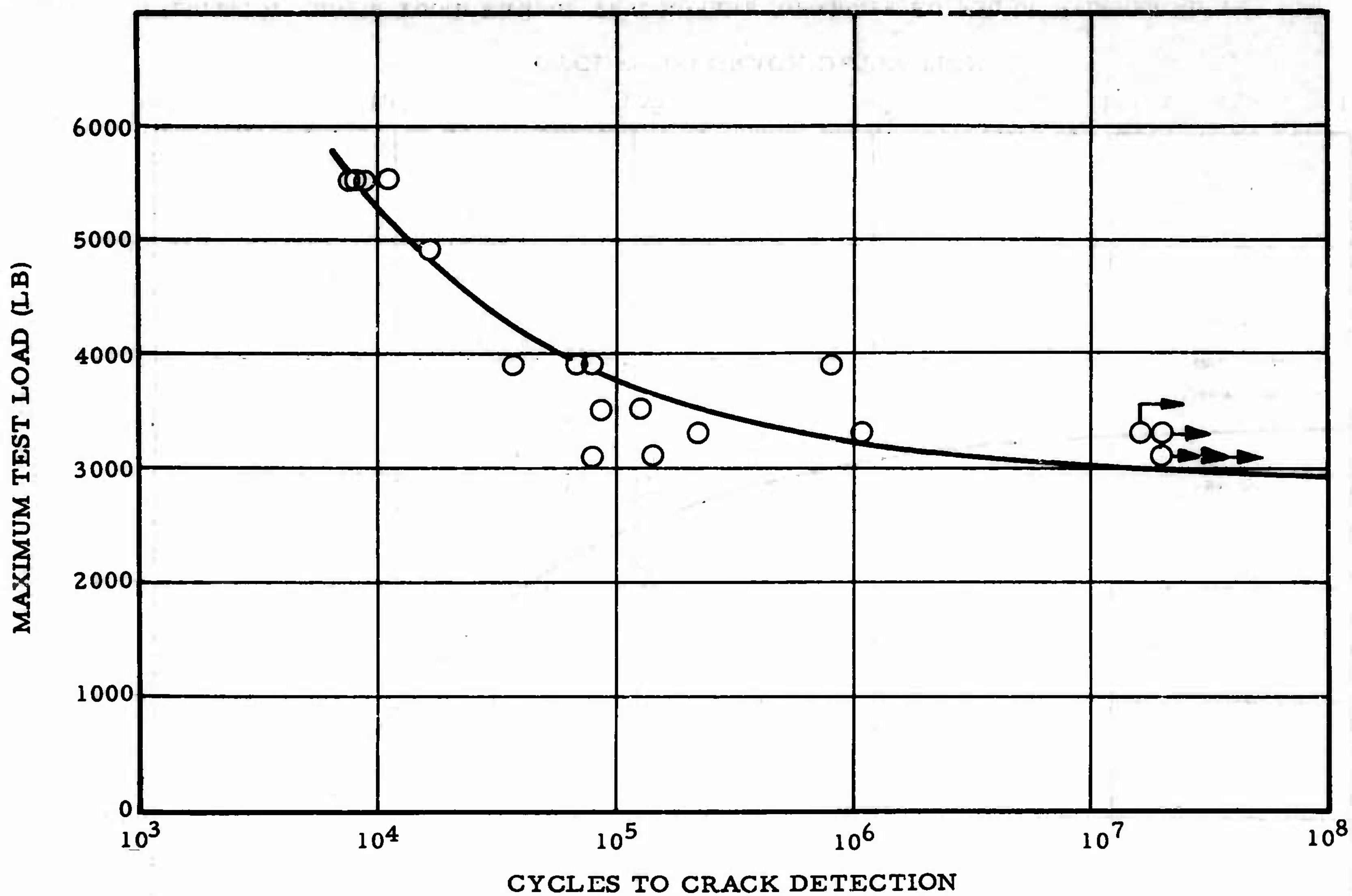


Figure 20. Single Tooth Fatigue Test Results for Gears Forged by Process "C".

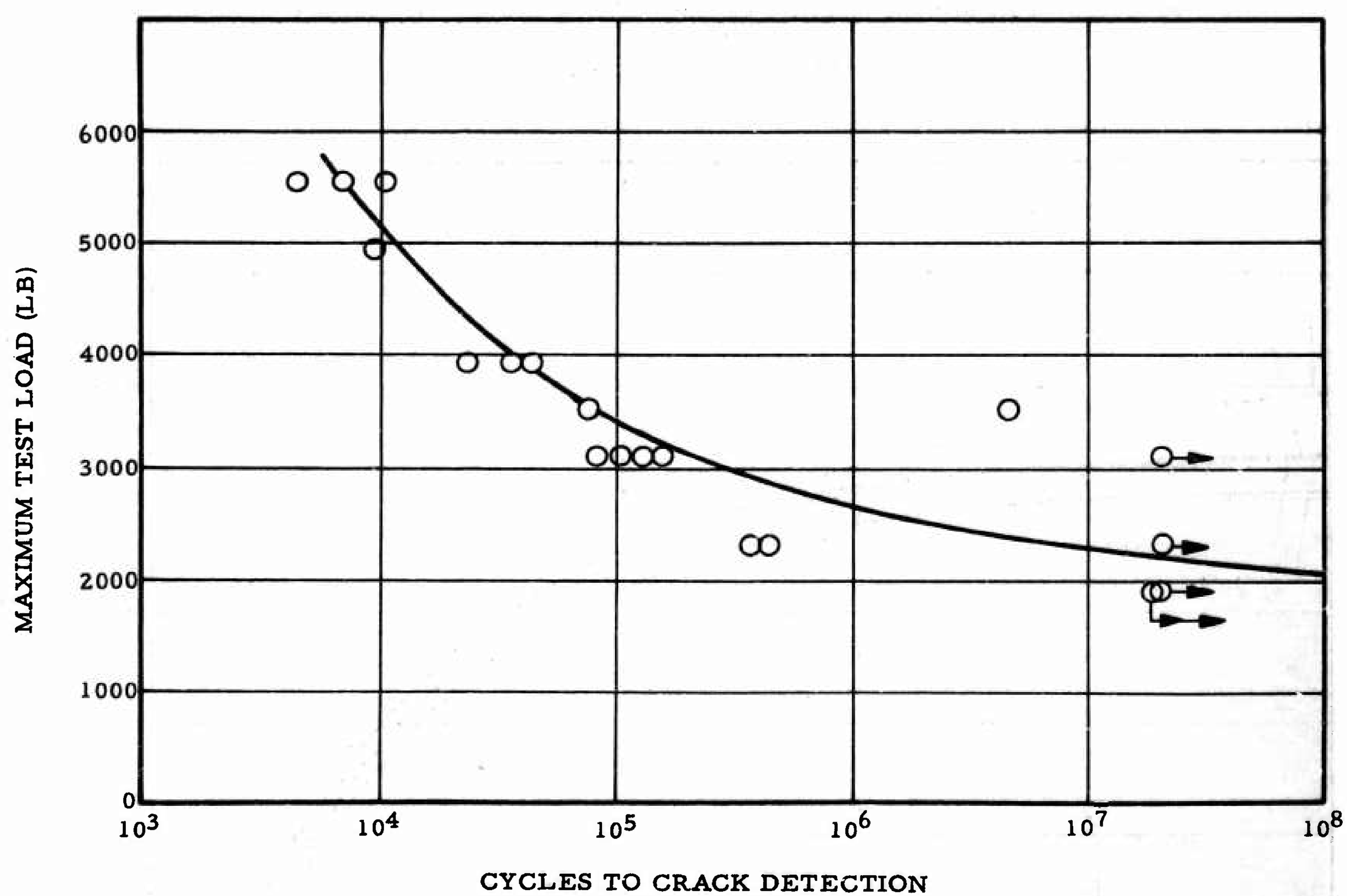


Figure 21. Single Tooth Fatigue Test Results for Conventionally Forged Gears.

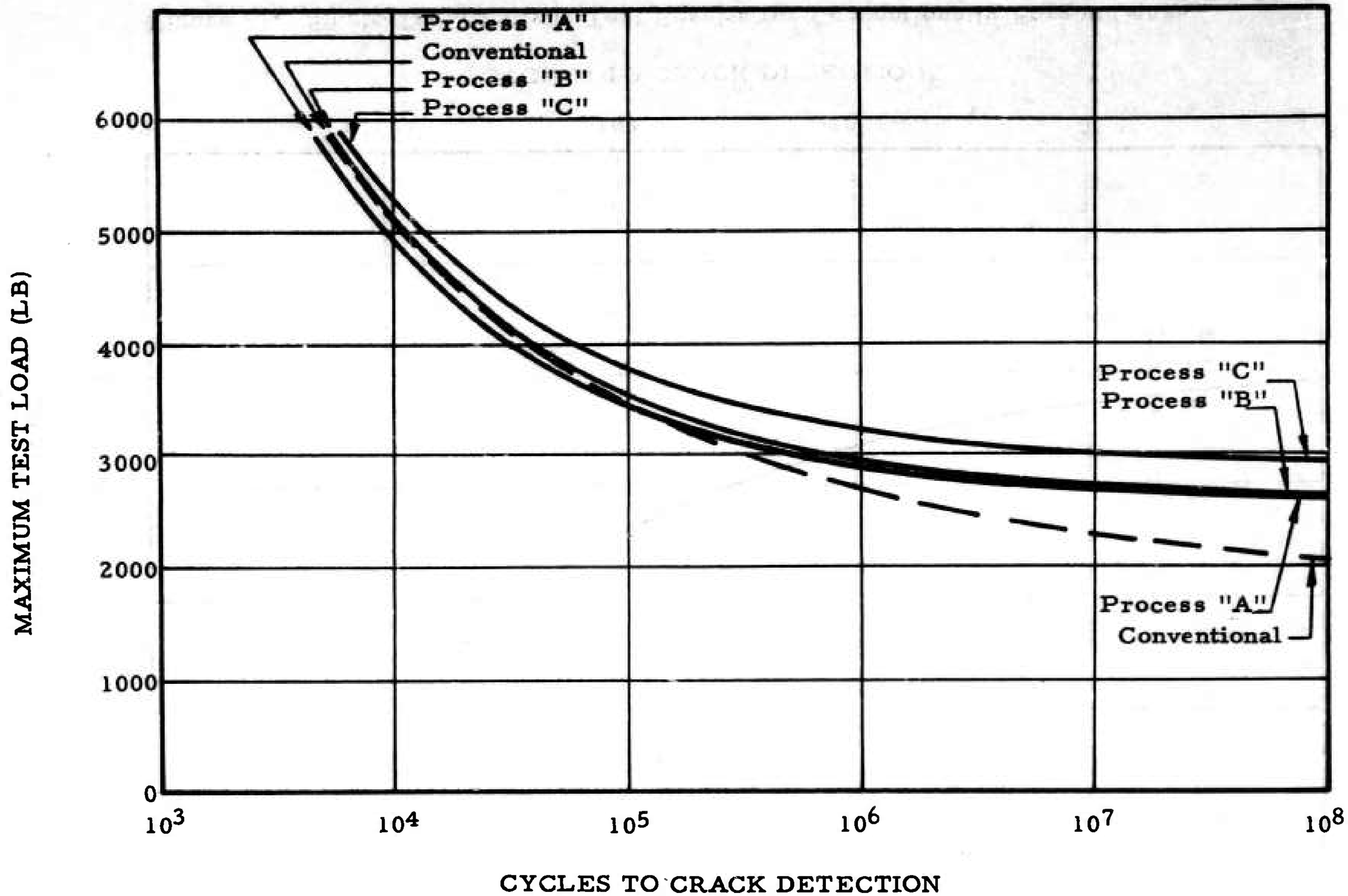


Figure 22. Composite of Mean Fatigue Curves for the Four Forging Processes.

TABLE V. FATIGUE TEST RESULTS

Forging Process	No. of Test Points (n)	$\bar{E}_t$ (lb)	α	β	$\bar{X}$* (lb)	S* (lb)	$S/\bar{X}$ (%)	Mean Fatigue Strength** (%)
"A"	20	2540	.435	.125	2580	201	7.8	124
"B"	20	2570	.435	.125	2610	328	12.5	125
"C"	20	2940	.45	.100	2980	258	8.7	144
Conventional	20	1920	.325	.378	2080	387	18.6	100

*Applicable at 10^8 Cycles of Vibratory Stress.

**Relative to the Conventional Gears at 10^8 Cycles.

TABLE VI. RESULTS OF STATISTICAL TESTS ON MEAN STRENGTHS AT 10^8 CYCLES

Variables Compared	$\overline{X}$ (lb)	S (lb)	n	Results of Single-Tailed "t" Test
Conventional	2080	387	20	The mean fatigue strength of the gears forged by process "A" is at least 368 lbs higher than the mean fatigue strength of the conventional forged gears.
vs.				
Process "A"	2580	201	20	
Conventional	2080	387	20	The mean fatigue strength of the gears forged by process "B" is at least 366 lbs higher than the mean fatigue strength of the conventional forged gears.
vs.				
Process "B"	2610	328	20	
Conventional	2080	387	20	The mean fatigue strength of the gears forged by process "C" is at least 766 lbs higher than the mean fatigue strength of the conventional forged gears.
vs.				
Process "C"	2980	258	20	

TABLE VII. TEST DATA, SINGLE TOOTH STATIC TEST			
Forging Process	Serial No.	Tooth No.	Ultimate Load Applied at Tip of Tooth (lb)
"A"	01	A	7700
		D	8130
	03	A	7410
		C	7350
		D	7540
	05	A	8230
		B	8200
		D	8380
"B"	11	A	7140
		C	6960
		D	6620
	14	B	7270
	15	A	7480
		B	7400
		C	7030
		D	7140
"C"	25	A	7200
		B	7620
		C	8200
		D	7800
	28	A	8040
		B	7800
		C	7680
		D	7140
Conventional	31	A	8020
		B	7730
		C	8080
		D	8810
	35	A	6600
		B	6380
		C	6920
		D	7010

TABLE VIII. RESULTS OF STATISTICAL TESTS ON STATIC TEST DATA

Variables Compared	$\bar{X}$ (lb)	S (lb)	$S/\bar{X}$ (%)	n	Results of Single-Tailed "t" Test
Conventional	7440	844	11.34	8	The mean ultimate static strength of the gears forged by process "A" IS NOT significantly different from the mean of the conventionally forged gears.
vs.					
Process "A"	7870	411	5.23	8	
Conventional	7440	844	11.34	8	The mean ultimate static strength of the gears forged by process "B" IS NOT significantly different from the mean of the conventionally forged gears.
vs.					
Process "B"	7130	271	3.8	8	
Conventional	7440	844	11.34	8	The mean ultimate static strength of the gears forged by process "C" IS NOT significantly different from the mean of the conventionally forged gears.
vs.					
Process "C"	7690	369	4.8	8	

METALLURGICAL STUDY

INVESTIGATION PROCEDURE

Metallurgical investigations were conducted to determine the mode of failure, origin of failure, microstructure of the case and core, chemical composition, grain size, grain flow, case depth, and hardness of the case and core. The investigations were conducted as follows:

1. All fractured teeth were examined under a low-power stereomicroscope to determine the mode and origin of failure.

2. One fractured tooth from each test gear was further examined as follows:

   a. The Rockwell hardness (R_c) was determined for the case and core.

   b. The fractured teeth were mounted, polished, etched with a 2 percent Nital solution, and examined on a metallograph to determine the microstructure of the case and core.

   c. The tctal case depth was determined by examination of the etched mounts under a Brinell microscope. The effective case depth was determined on a Tukon that had been microhardness tested for one tooth from each forging process. The case-core transition point was taken at Rockwell R_c 50.

3. One gear from each forging process was analyzed on a spectrograph to determine the chemical composition. A volumetric carbon determination of the core was also conducted.

4. Grain flow was determined for a series of gear teeth from each of the high energy gears in the as-forged condition and for all four processes after heat treating and finish grinding. Transverse sections were cut from the gear teeth, mounted, and polished. After considerable experimentation, a saturated solution of ammonium persulfate in water was found to be the best etchant for revealing the flow lines. A final polishing with 1-micron diamond paste was necessary after etching to bring out the flow lines satisfactorily. Repeated etching and polishing were frequently necessary to obtain sufficient contrast.

5. Prior austenitic grain size was determined on a series of gear teeth from each forging process using the McQuaid-Ehn test.

Heat treatment was carried out in a carbonaceous atmosphere at 1,600°F for 10 hours, followed by furnace cooling. A solution of Nital and Picral was found to reveal the grain size better than either of the etchants individually. The ASTM grain size was determined by comparison with standard ASTM grain size charts at a 100X magnification.

FRACTURE ANALYSIS

Examination of the fatigue-tested gear teeth fracture surfaces revealed similar fractures for all forging processes. Figure 23 illustrates typical fracture surfaces with fatigue origins indicated for each forging process. Predominately multiple origins were determined, originating at the surface of the carburized case at the start of the root radius. The multiple origins indicate that uniform loading was obtained across the tooth surface.

Figure 24 shows a typical static fracture surface. The fracture interface is considerably more crystalline and coarse than the fatigue fracture surfaces.

HARDNESS AND CASE DEPTH

Hardness (Rockwell R_c) readings for the case and core and the case depth are listed in Table IX. The results show that all teeth evaluated were equivalent in both hardness and case depth and were within the drawing requirements. A typical microhardness traverse is shown in Figure 25. The uniformly decreasing hardness gradient with no sharp dropoff (typical of all the gears checked) shows that a good carburized case was present. The effective case depths, which were obtained from the microhardness traverses, agreed with the total case depths determined by optical means.

CHEMICAL ANALYSIS

The chemical analyses for one gear from each forging process are given in Table X. Included in this table is the material composition requirement of AMS 6260, Reference 4. The results show that the material composition for each forging process is essentially identical and within the specification requirements. These results indicate that the gears were fabricated from the same heat of material as required by the test program.

MICROSTRUCTURE

The microstructures shown in Figures 26 and 27 are typical of those found in all of the test teeth examined. There were no differences found between individual gears or forging processes. The case and core microstructures

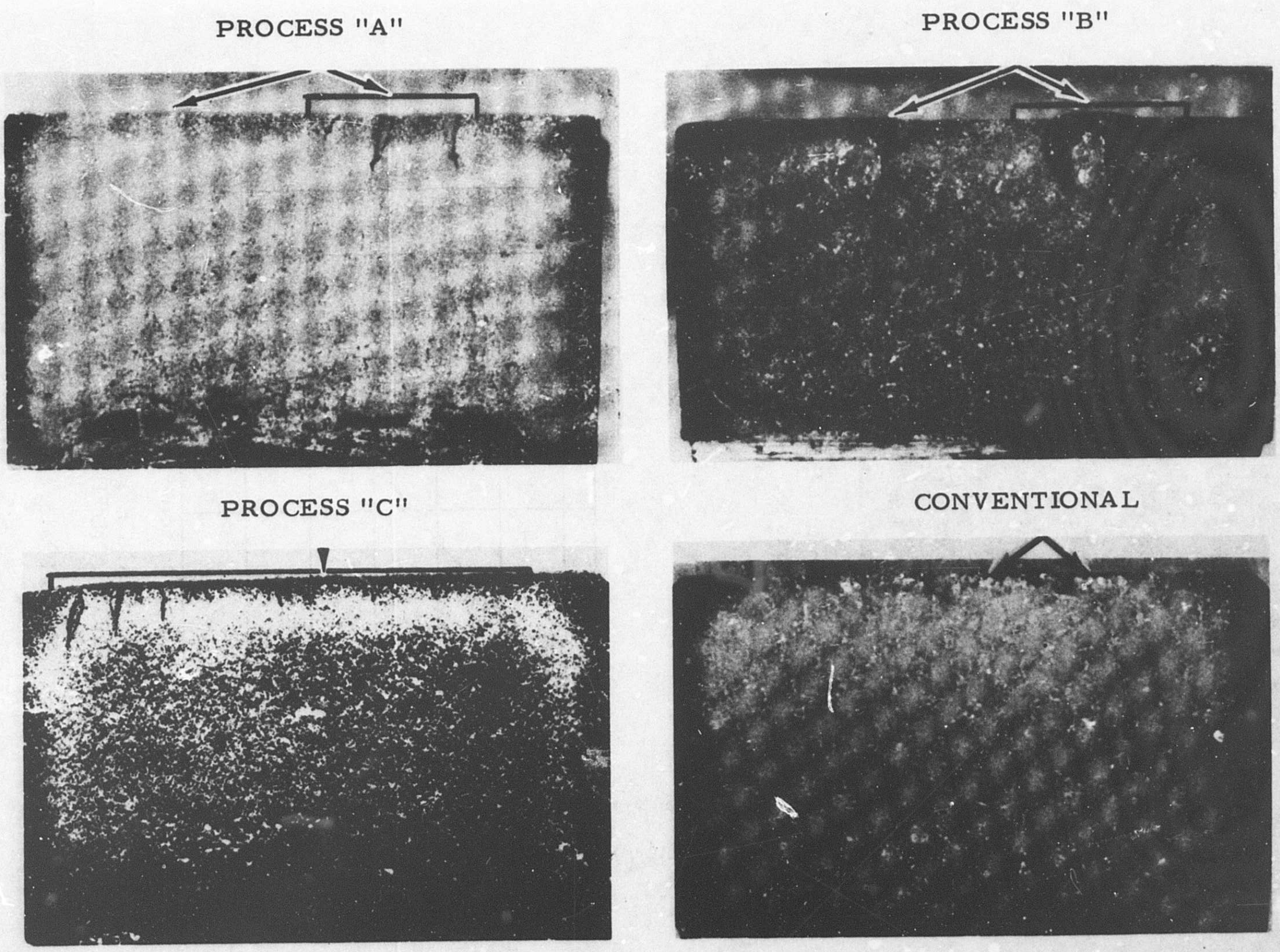


Figure 23. Typical Fatigue Fracture Surfaces (Arrows Indicate Origins of Failure).

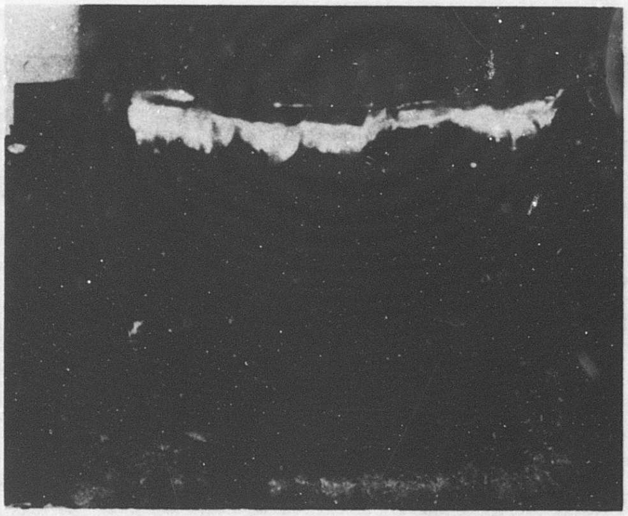


Figure 24. Typical Static Fracture Surface.

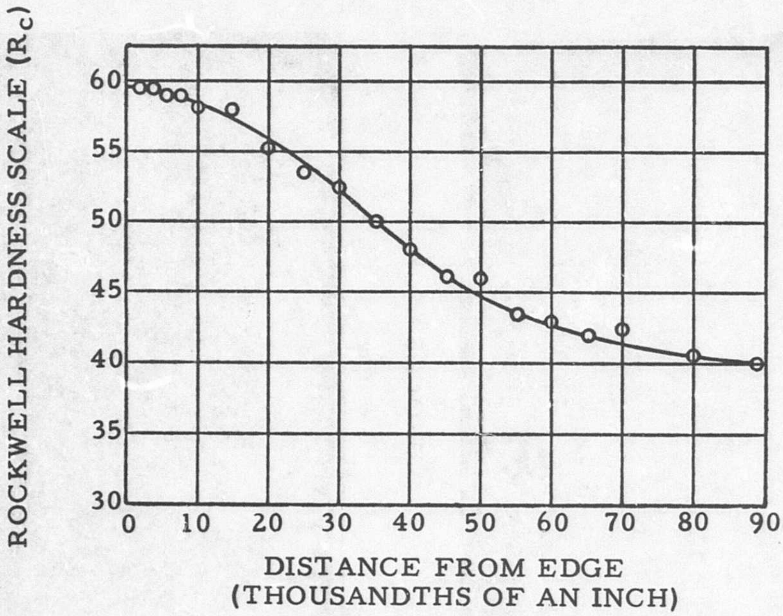


Figure 25. Typical Microhardness Reading.

TABLE IX. SUMMARY OF GEAR HARDNESS AND CASE DEPTH RESULTS

Forging Process	Serial No. Fatigue	Serial No. Static	Rockwell Hardness (R_C) Case	Rockwell Hardness (R_C) Core	Case Depth (in.) Total (Visual)	Case Depth (in.) Effective (Depth to R_C - 50)
	03		59-60	39	.038-.040	
	04		58-61	39	.036-.038	
	06		60	36-37	.036-.040	
"A"	07		59-61	38	.036-.038	.035
	09		60	38	.036	
		01	59-60	38	.036-.038	
		03	59	37	.036-.038	
		05	58-60	38	.036-.040	
	12		60-61	36-39	.036-.040	
	13		59	37-38	.036-.038	
	15		60-61	37-38	.036-.040	
"B"	16		60	37	.036-.038	.035
	20		59-60	35-36	.036-.040	
		11	58-59	38	.036-.038	
		14	60-61	36-38	.036-.038	
		15	59-60	37	.036-.040	
	23		59-60	37-38	.036-.038	
	24		59-60	37-38	.036-.038	
"C"	26		60	38	.036-.040	
	27		59-60	38	.036-.040	.035
	28		60	38	.036-.038	
	29		59-61	39	.036-.040	
		25	59-60	39	.036-.040	
		28	58-60	36	.036-.040	
	32		58-60	39	.040	
	33		59-60	40	.038	
Conventional	34		60	40	.036	
	37		60-61	40	.036-.038	.035
	38		60-61	40	.036-.040	
		31	59-60	36	.036-.038	
		35	58-60	38	.036-.040	
Drawing Requirement			58-64	34-40	.035-.045	

TABLE X. CHEMICAL ANALYSIS

Forging Process	% by Weight						
	C	Mn	Si	Ni	Cr	Mo	Fe
"A"	0.12	0.70	0.29	3.20	1.36	0.12	Bal.
"B"	0.12	0.70	0.29	3.30	1.33	0.12	Bal.
"C"	0.12	0.68	0.28	3.25	1.27	0.12	Bal.
Conventional	0.12	0.68	0.29	3.20	1.32	0.12	Bal.
Drawing Requirement (AMS 6260G)	0.07 to 0.13	0.40 to 0.70	0.20 to 0.35	3.00 to 3.50	1.00 to 1.45	0.08 to 0.15	Bal.

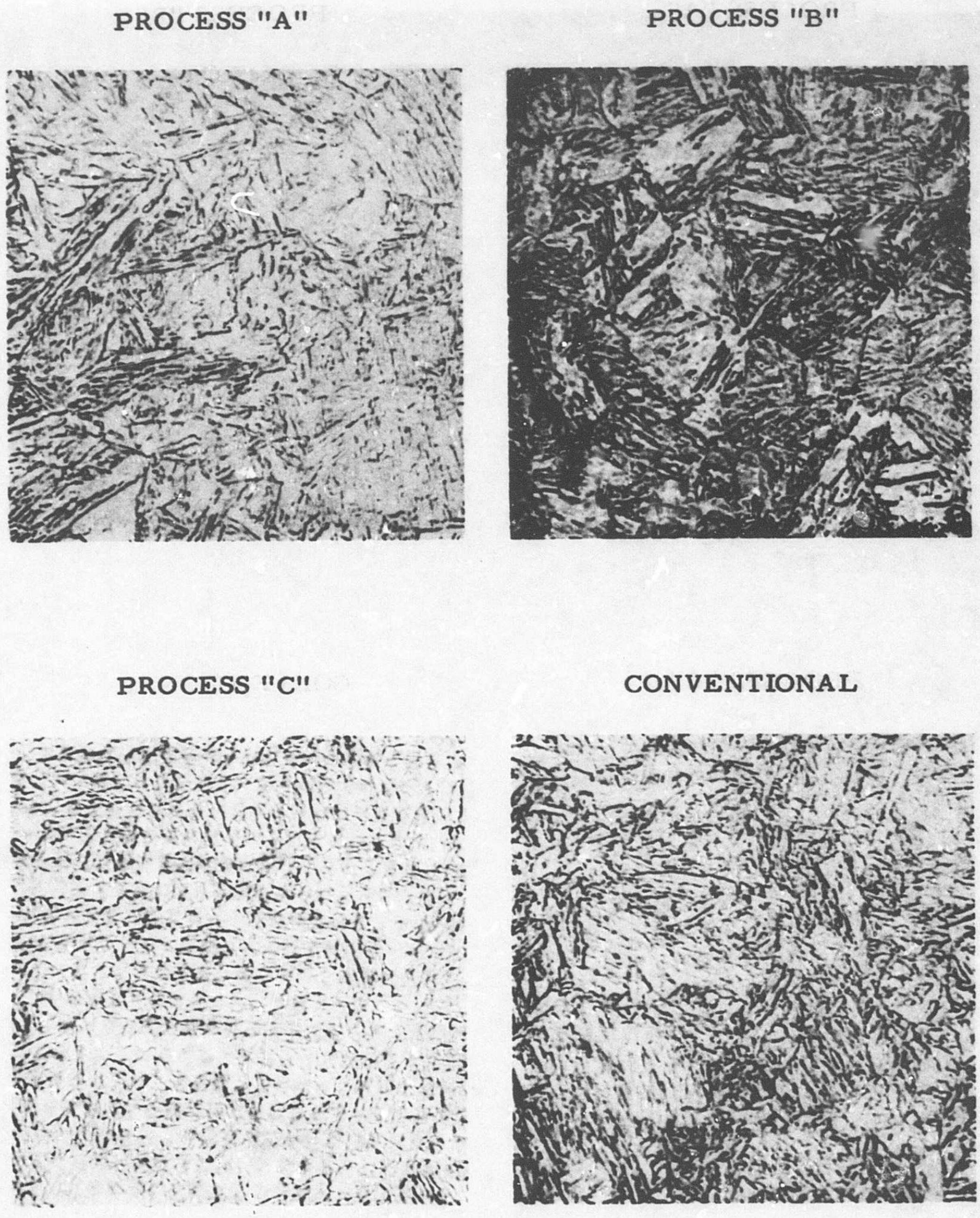
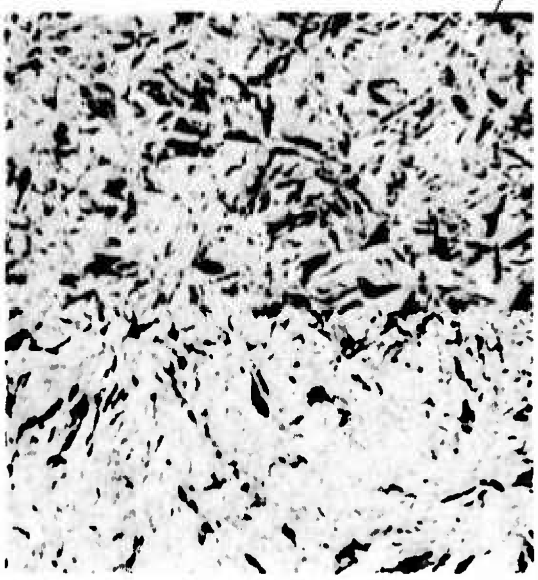


Figure 26. Typical Case Microstructure for the Four Gear Forging Processes.

PROCESS "A"



PROCESS "B"

PROCESS "C"

CONVENTIONAL

Figure 27. Typical Core Microstructure for the Four Gear Forging Processes.

of tempered martensite are in accordance with the requirements of MIL-H-6875, Reference 5, with no abnormalities visible at 500X magnification.

GRAIN FLOW ANALYSIS

Figures 28 through 30 show the grain flow of the high energy forged gear teeth in the as-forged condition. Continuous flow lines around the critical root area to a depth of at least .020 inch are evident. (It is extremely difficult to measure the actual depth of flow since the line of demarcation is not clearly defined.) Flow lines continue along the profile of the teeth and dissipate at the top land in all three of the high energy forged gears. A conventional pancake forging in the as-forged condition was not analyzed for grain flow since the gear teeth were not integrally forged. Figure 31 shows the grain flow for the conventional gear teeth after final grinding. In all three high energy processes, some of the flow lines in the root area were cut during grinding. Arrows in Figure 32 indicate the extent to which this occurred. The radiating flow lines from the center of the gear with no continuous flow lines around the critical root areas are typical of conventional gears. The finished gear teeth on the high energy forgings reveal the same flow as was visible in the as-forged gear teeth. The grain flow pattern was unaffected by the phase transformation that occurred during the carburizing process as shown in Figures 33 through 35.

It appears that the process "C" gears had fewer flow lines coming to the surface, and they were concentrated in the lowest portion of the root radius. Process "A" and "B" gears showed flow lines coming to the surface over most of the root radius, almost to the point of maximum stress on the tooth profile where failures generally occurred. This condition might account for the higher fatigue strength exhibited by the gears forged by process "C".

GRAIN SIZE

The prior austenitic grain size was found to be the same for all four forging processes and equivalent to an ASTM grain size of 7 or 8 as determined by comparison to ASTM standard charts at 100X magnification. This grain size is within the requirements of AMS 6265, Reference 3, which calls for a grain size of 5 or finer. Figure 36 shows the grains of a typical specimen as revealed by the McQuaid-Ehn test. Although grain size determination was conducted at 100X magnification, because of the very fine grains of this material, Figure 36 is presented at 1,000X magnification for clarity.

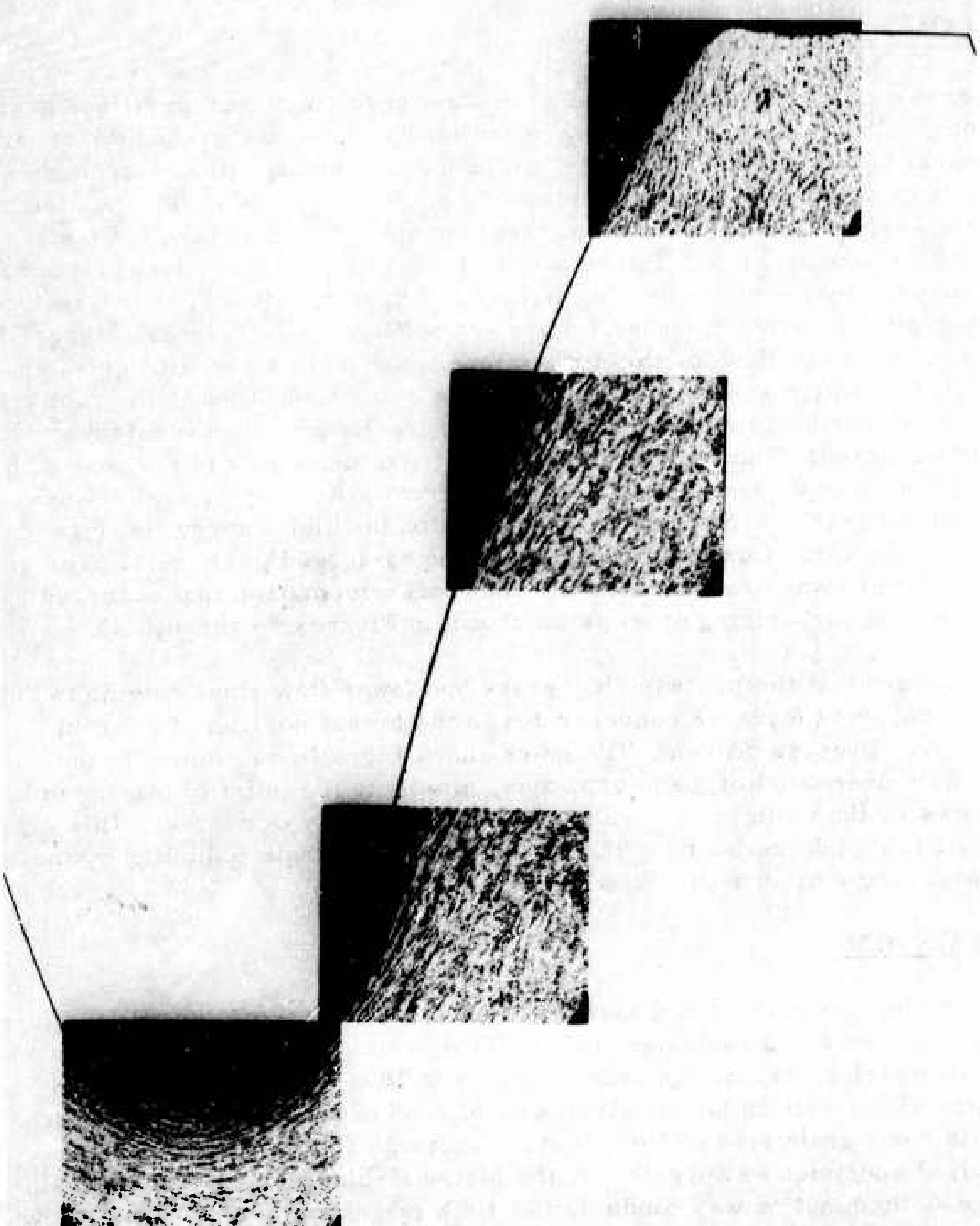


Figure 28. Grain Flow of As-Forged Gear - Process "A".

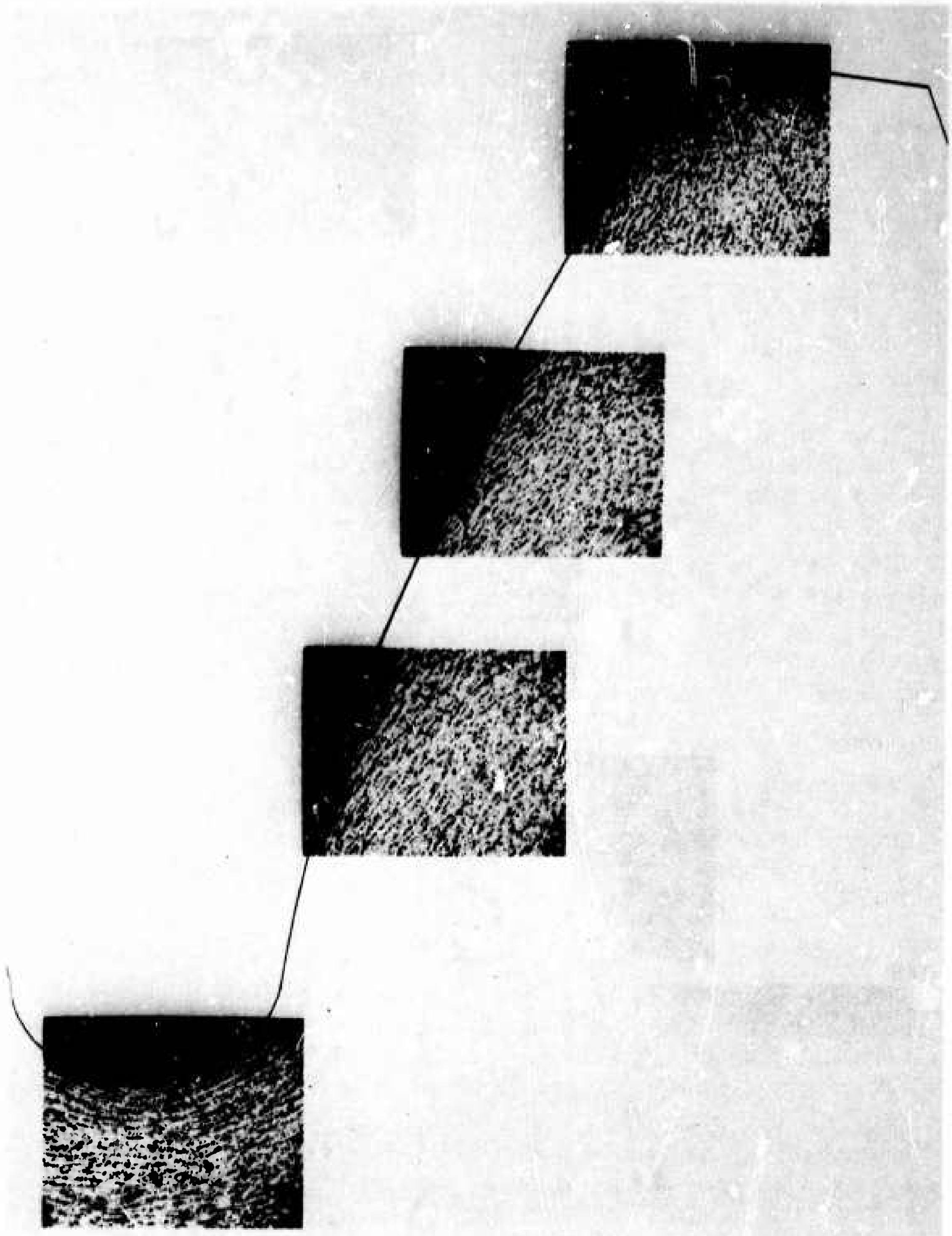


Figure 29. Grain Flow of As-Forged Gear - Process "B".

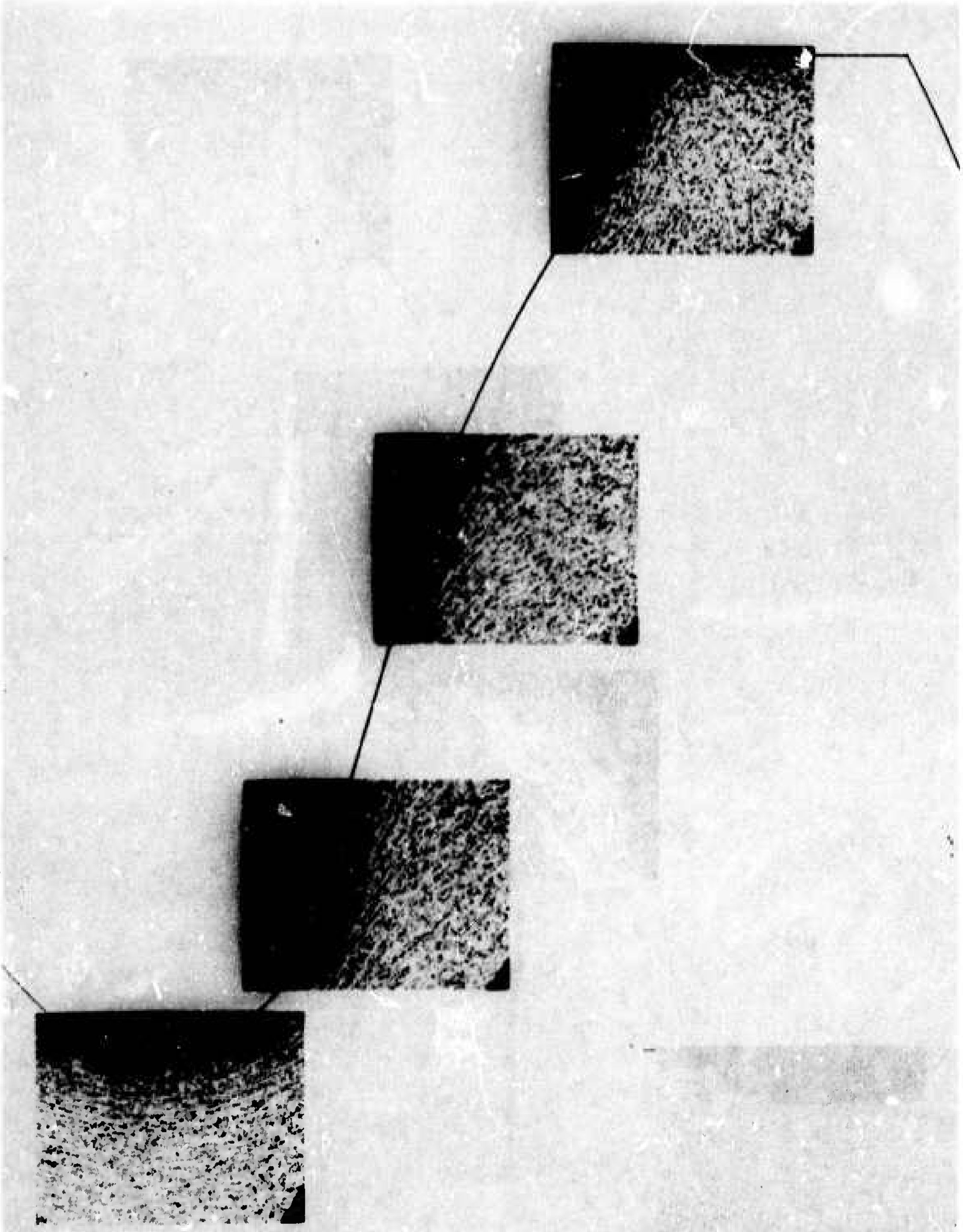


Figure 30. Grain Flow of As-Forged Gear - Process "C".

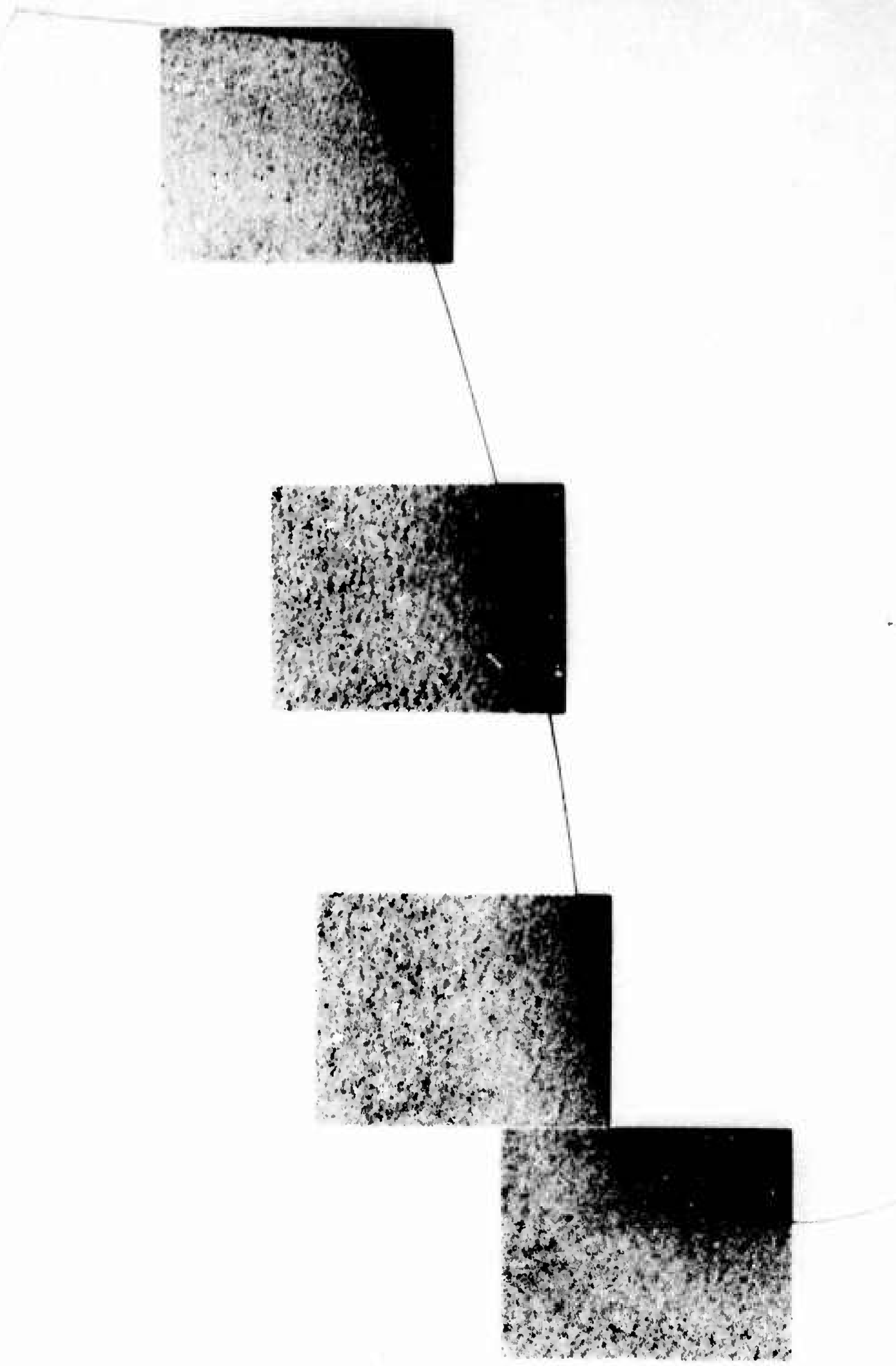


Figure 31. Grain Flow of Finished Gear - Conventional Method.

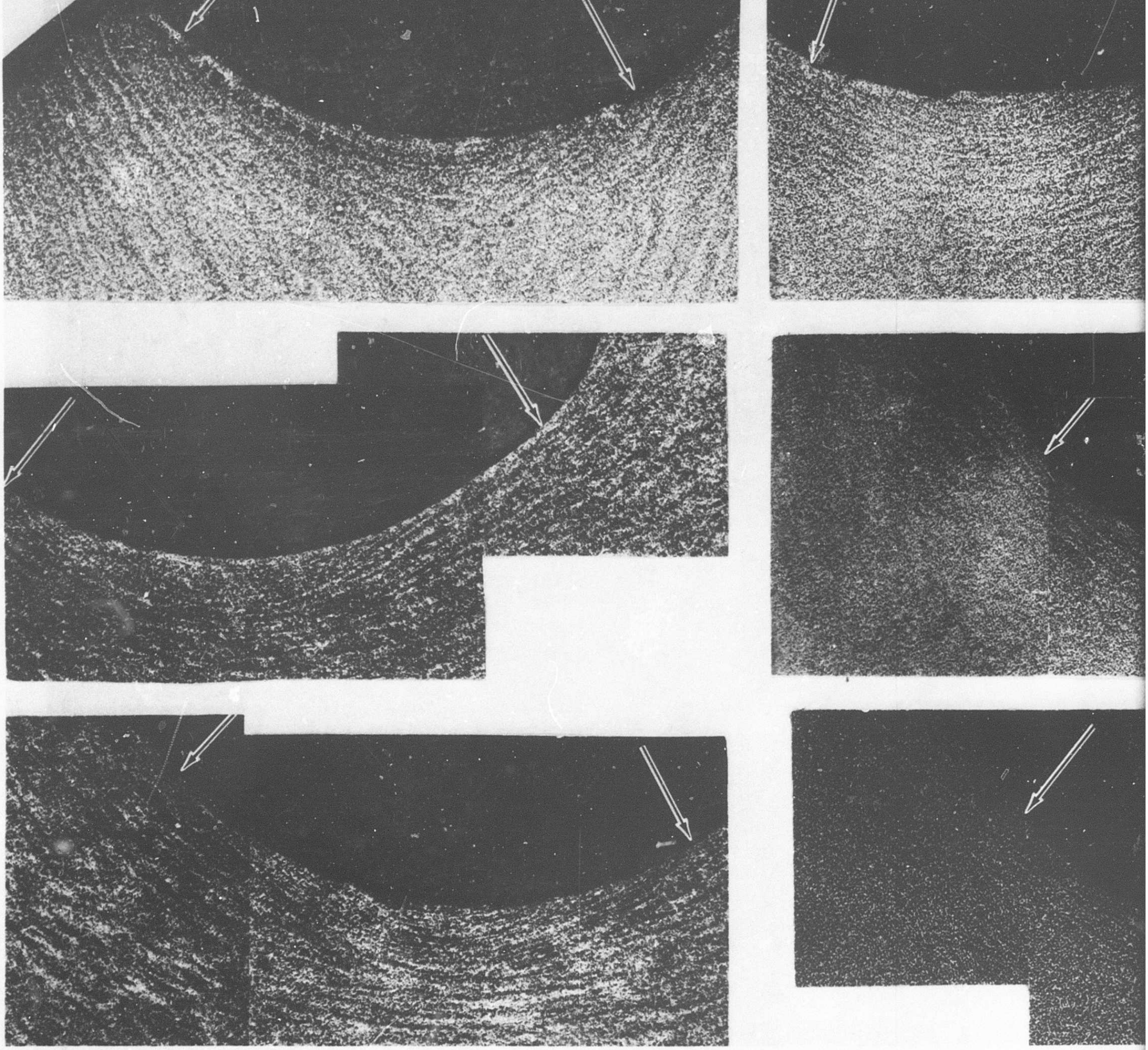
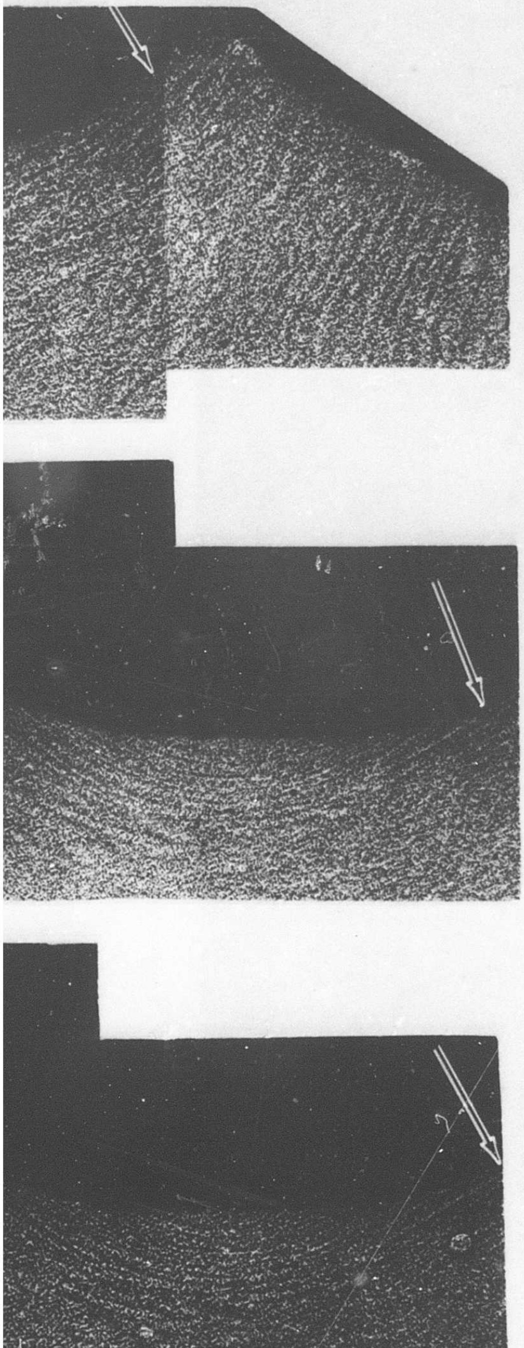


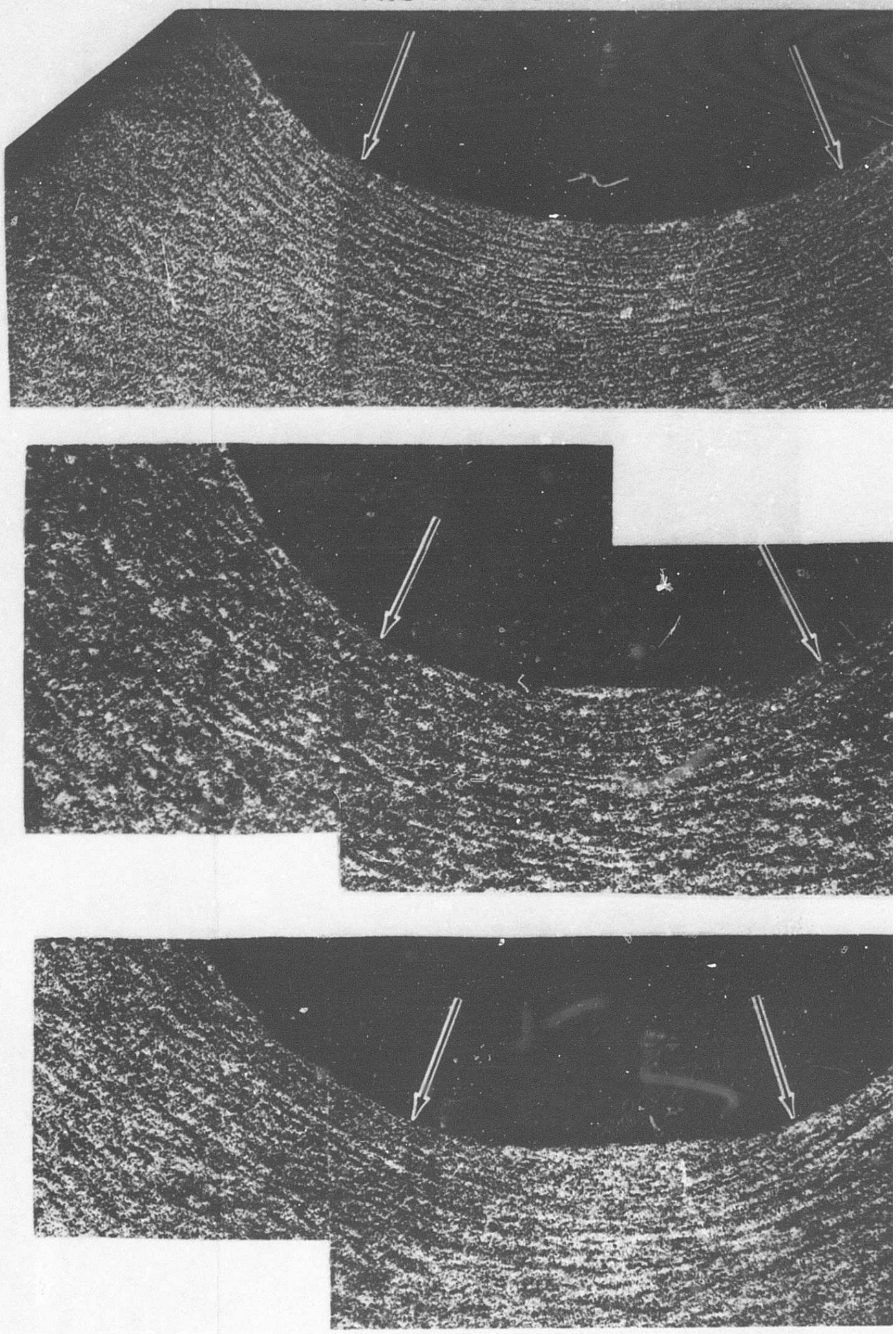
Figure 32. View in Root Sections, 40X.

A

CESS "B"



PROCESS "C"



B

BLANK PAGE

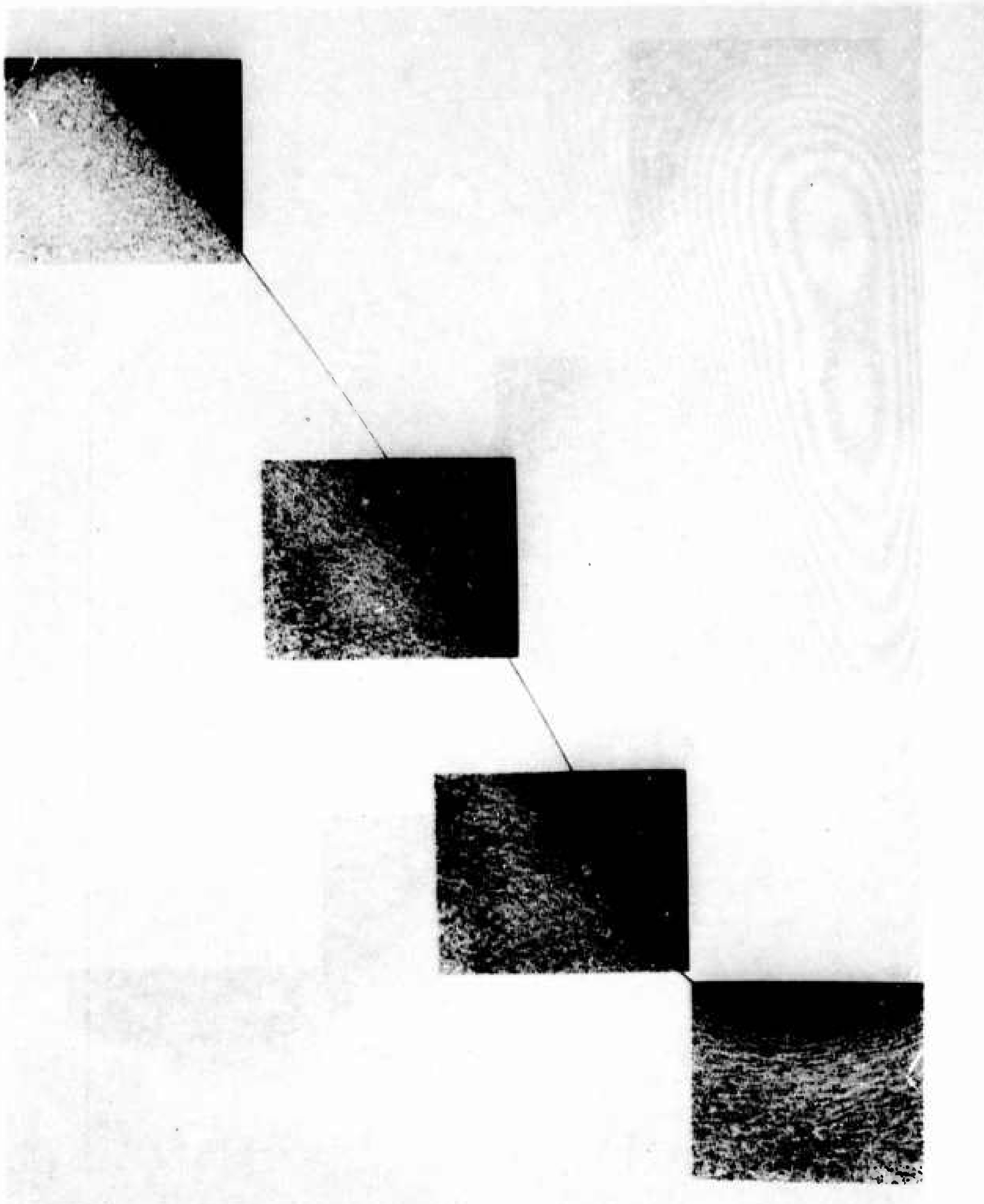


Figure 33. Grain Flow of Finished Gear - Process "A".

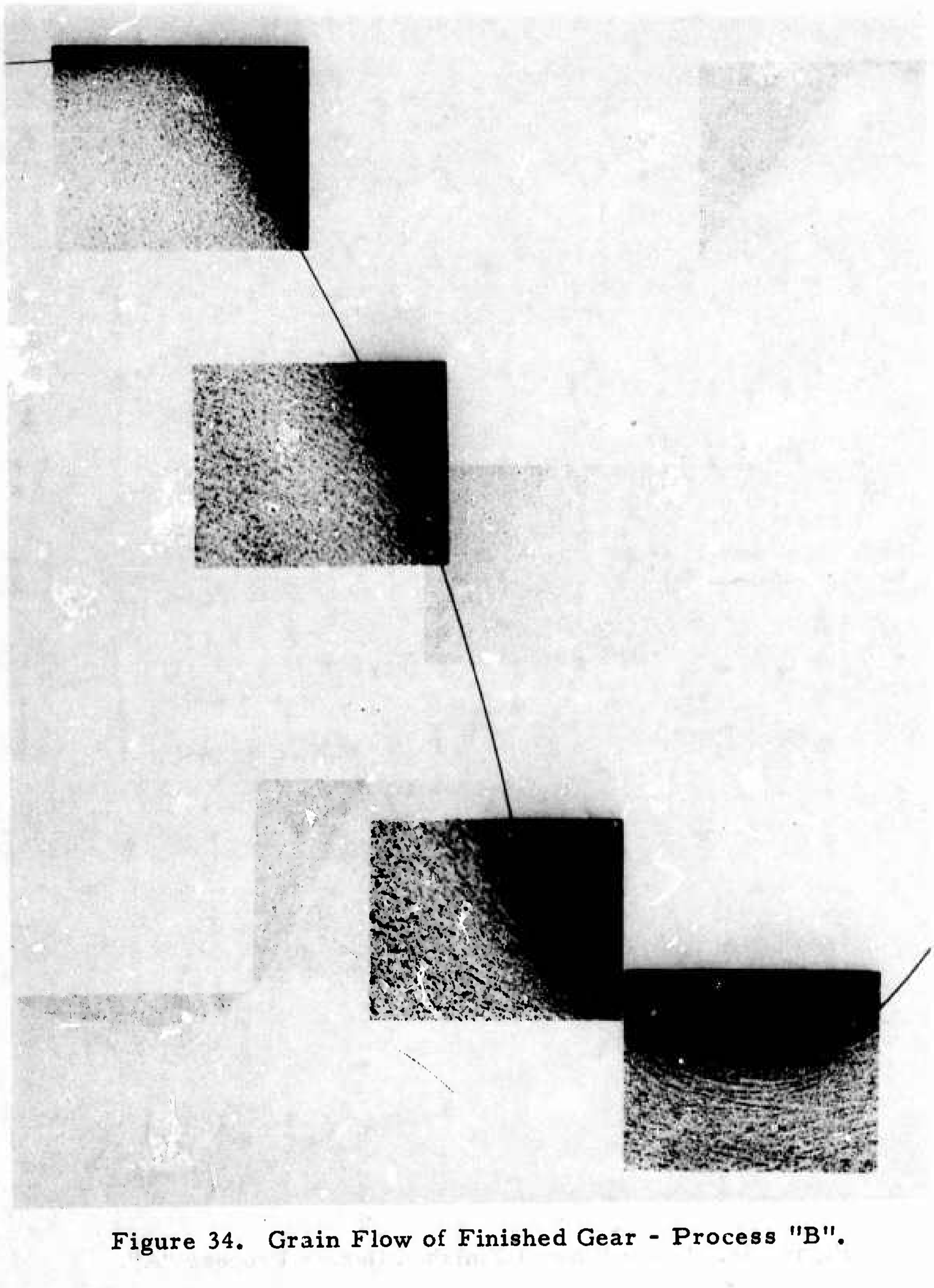


Figure 34. Grain Flow of Finished Gear - Process "B".

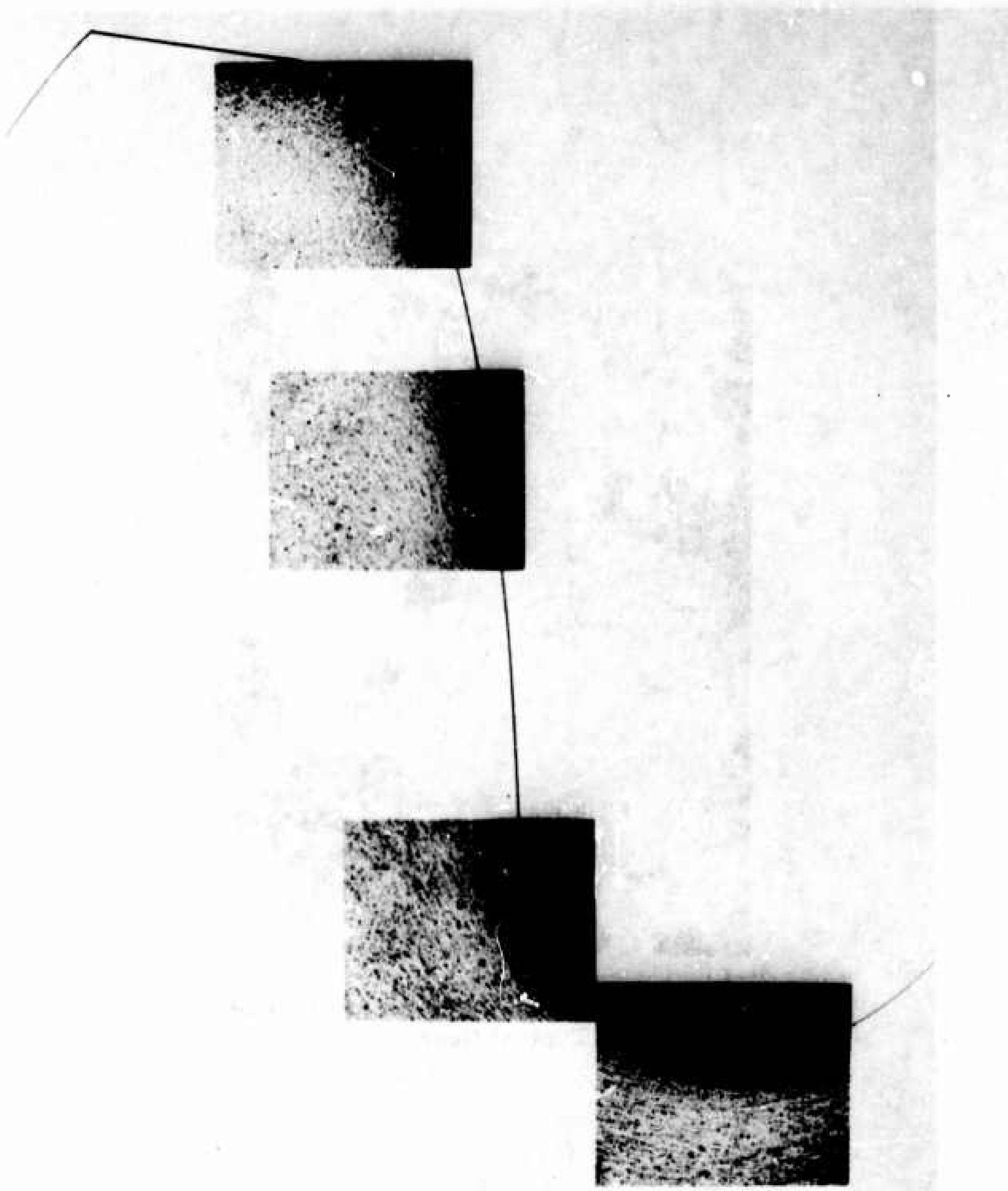


Figure 35. Grain Flow of Finished Gear - Process "C".

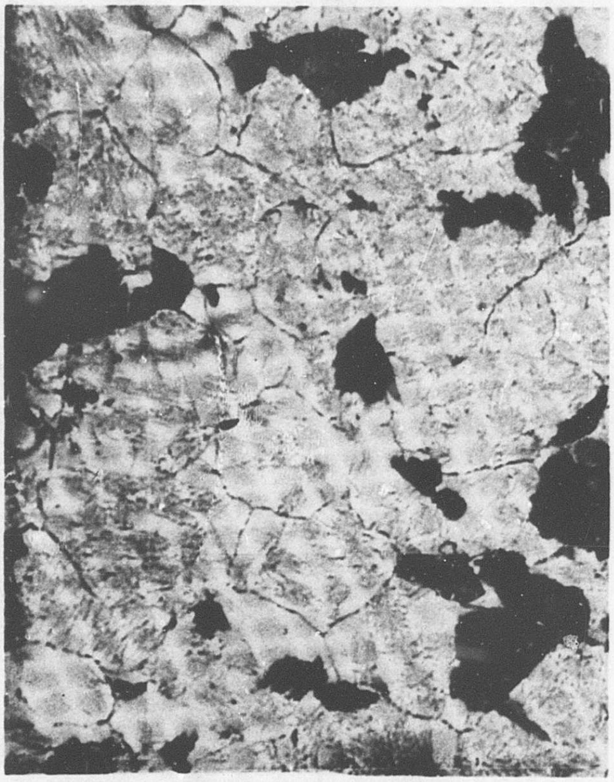


Figure 36. Prior Austenitic Grain Size, Typical Gear.

DATA EVALUATION

FATIGUE ANALYSIS

The fatigue data were analyzed statistically, and parameters were determined as follows: At each load level (example: 3,900 pounds), the logarithmic mean of the cycles to crack detection was determined. A best-fitting, smooth curve was drawn through these logarithmic mean points. Two coordinate points of this mean curve plus E_s, the estimated mean endurance strength at an infinite number of cycles, were substituted in a curve shape equation of the form

$$Pm = E_s + \alpha/N^{\gamma}$$

The constants of the equation (α and γ) were then determined. Once these constants were obtained, the full curve was calculated, plotted, and compared to the originally estimated curve. An iterative process was used to select the values of E_s, α, and γ, which when used in the above equation closely approximated the estimated mean curve. Once selected, these constants were converted for convenience into the form β and γ, where these values became the standard curve constants to be used for the subject set of test data. A Programma 101 Desk Top Computer was used in processing the individual test failure point coordinates, using the constants derived above, and the following equation:

$$E_t = Pm/1 + \beta/N^{\gamma}$$

The computer calculated the sample standard deviation, S, and the sample mean endurance strength at an infinite number of cycles, E_t, and the sample coefficient of variation, $S/\overline{X}$. The computer also calculated specific load and cycle intercepts of the mean curve. These values were used to draw the mean curves shown in this report. The standard deviation at 10^8 cycles was then calculated.

Using the calculated mean endurance strengths and the standard deviation at 10^8 cycles, single-tailed "t" tests were performed at a 90% confidence level to determine if a statistical difference existed in the mean cycles to crack detection between the conventional and either of the high energy processes at a constant load level.

The "t" tests were conducted following methods similar to those given in Reference 3. The results of these tests are shown in Table XI. The "t" test is used when the variances of the populations from which the samples were taken cannot be assumed as known. It is assumed, however, that the variances are equal. The single-tailed "t" test uses an alternative

TABLE XI. RESULTS OF STATISTICAL TESTS ON THE LOGARITHMIC MEAN CYCLES AT THE 5500-POUND TEST LEVEL

Variables Compared	Log Mean (lb)	Log S (lb)	n	Results of Single-Tailed "t" Test
Conventional vs.	6990	1530	3	The logarithmic means of the cycles to crack detection at the 5500-lb test level for the gears forged by process "A" and by conventional methods ARE NOT significantly different.
Process "A"	6230	1190	4	
Conventional vs.	6990	1530	3	The logarithmic means of the cycles to crack detection at the 5500-lb test level for the gears forged by process "B" and by conventional methods ARE NOT significantly different.
Process "B"	6760	1590	4	
Conventional vs.	6990	1530	3	The logarithmic means of the cycles to crack detection at the 5500-lb test level for the gears forged by process "C" and by conventional methods ARE NOT significantly different.
Process "C"	9370	1180	4	

hypothesis which seeks to show that one population mean is greater than another.

DESIGN ANALYSIS

It is of some interest to compare the current AGMA gear design standard with the results obtained in this test program. The present AGMA formula for describing the bending strength of a spur gear tooth is

$$Fb = Wt\ Ko\ Pd\ Ks\ Km/Kv\ F\ J\ psi$$

Single tooth fatigue testing is a nonrotating test, with the load applied normal to the involute, and arranged to make contact at the "highest point of single tooth contact". Referring to the above strength formula, it is reasonable to assume that

$$Ko = Kv = Ks = Km = 1.0$$

Then for the test gears described,

$$Fb = Wt\ Pd/F\ J\ psi$$

$$= Wt \times 8/.375 \times .42 = 50.8\ Wt\ psi$$

The applied loads and equivalent stress levels that were obtained at 10^8 cycles (approaching runout) have been calculated for each type of gear forging and are shown in Table XII.

TABLE XII. LOAD AND STRESS LEVELS AT 10^8 CYCLES

	Process "A"	Process "B"	Process "C"	Conventional
Test Load (lb)	2,580	2,610	2,980	2,080
Stress (psi)	121,500	123,000	140,000	97,800

The stresses quoted in Table XII are obviously not suitable for use in design equations for real gear applications. Many other factors must be taken into consideration. These factors would primarily include dynamic loading, misalignment errors, and casing deflection effects. Therefore, the stresses quoted in Table XII will require modification before they can be used by the gear designer as applicable design data.

CONCLUSIONS

1. Spur gears manufactured from blanks with integrally formed teeth produced by high energy forging techniques demonstrate higher fatigue strengths than cut and ground gears made from conventional pancake forgings. On the basis of single tooth fatigue tests, the high energy formed gears had endurance limits (at ten million cycles) that are from 24 to 44 percent higher than the conventionally forged gears.

2. There is no appreciable difference in static or low cycle fatigue strengths of the high energy and conventionally forged gears.

3. The metallurgical properties such as microstructure, grain size, case depth, and core hardness of all gears tested (high energy and conventionally forged) are essentially the same. The improvement in fatigue strength therefore appears to be due to the orientation of the grain flow in the advanced (or high energy) gears. In these gears, the grain flow follows the gear tooth profile.

4. While the results of the single tooth tests are indicative of the possible improvements afforded by high energy gear forging techniques, the present data cannot be directly converted into design allowables for actual gear applications.

LITERATURE CITED

1. Parkinson, Fred L., EVALUATION OF HIGH ENERGY RATE FORGED GEARS WITH INTEGRAL TEETH, Western Gear Corporation; USAAVLABS Technical Report 67-11, U.S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia, March 1967, AD 651316.

2. Dudley, Darle W., PRACTICAL GEAR DESIGN, New York, Toronto, London, McGraw-Hill Book Company Inc., 1954, p. 44.

3. AMS-6265B AEROSPACE MATERIAL SPECIFICATION, Steel Bars, Forgings and Tubing, 0.12 Mo (0.07-0.13C) (SAE 9310) Premium Quality.

4. Hald, A., STATISTICAL THEORY WITH ENGINEERING APPLICATIONS, New York, John Wiley and Sons Inc., 1952.

5. MIL-H-6875D, Military Specification - Heat Treatment of Steels, March 1967.

UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Sikorsky Aircraft, Division of United Aircraft Corporation Stratford, Connecticut	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

EVALUATION OF ADVANCED GEAR-FORGING TECHNIQUES

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Final Report

5. AUTHOR(S) *(First name, middle initial, last name)*

Lester R. Burroughs
Paul C. FitzGerald

6. REPORT DATE April 1969	7a. TOTAL NO. OF PAGES 72	7b. NO. OF REFS 5

8a. CONTRACT OR GRANT NO. DAAJ02-67-C-0014	9a. ORIGINATOR'S REPORT NUMBER(S) USAAVLABS Technical Report 69-11
b. PROJECT NO. Task 1G162204A01410	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* Sikorsky Engineering Report 50560
d.	

10. DISTRIBUTION STATEMENT

[redacted]

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U.S. Army Aviation Materiel Laboratories, Fort Eustis, Virginia

13. ABSTRACT

The results of a gear fatigue research program, which extended over an 18-month period, are reported herein. The purpose of this research effort was to compare both the fatigue and static bending strengths of spur gear teeth manufactured by various advanced forging processes and one conventional forging process. ( )

All of the advanced forging processes used a similar method of fabrication, in that they incorporated high energy rate forging techniques. The types of press and design of the dies were different for the three advanced processes. However, the as-forged gear blanks were similar except for some variations in the flash formation.

On the basis of the results obtained, it is concluded that spur gears fabricated from forgings which produce integrally forged teeth have higher fatigue strengths than conventionally cut and ground gears made from pancake forgings. Increases in endurance limit were found to vary from 24 percent to 44 percent when comparing the integrally forged gear teeth with the conventionally produced gears.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Gears						
Gear Testing						
Metallurgy						
Gear Materials						
Gear Forgings						
Gear-Forging Techniques						
High Energy Rate Forging						

DD FORM 1 NOV 65 1473