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EVALUATION OF ADVANCED GEAR MATERIALS FOR GEAR BOXES AND TRANSMISSIONS

Final Report

(29 August 1968 to 28 October 1970)

October 1970

by

J. P. Alberti

A. J. Lemanski

Prepared Under Contract N00156-69-C-0634

for

Naval Air Propulsion Test Center

Department of the Navy

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by

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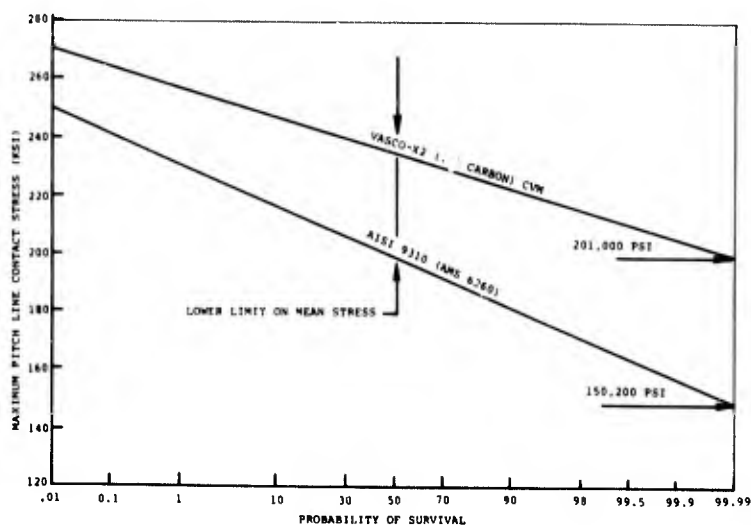
SUMMARY

The purpose of this project was to investigate the surface load carrying capability of one candidate advanced gear material by carrying out a program of experimental investigation to assess its resistance to surface fatigue (pitting and spalling).

This report presents the results of an experimental test program for evaluating the surface load capacity of VASCO-X2 (.24 carbon) high hot hardness tool steel spur gears and baseline spur gears fabricated from the currently used AISI 9310 (AMS 6260) aircraft gear steel.

The test program consisted of conducting rotating load tests on gear specimens of 5.333 diametral pitch, 4.50 and 7.50-inches pinion and gear pitch diameters respectively, 0.5-inch face width, form ground full circular fillets, case carburized, and heat treated to aircraft quality standards. The tooth geometry was designed to achieve pitting and spalling as the predominate failure mode under overload conditions. Ten test data points were achieved for each of the two materials under evaluation.

A summary of the mean endurance limits derived from the test data points for both materials is shown in the figure below:



Summary of Mean Endurance Limits
Derived from Test Data Points.

The conclusions of this report are summarized as follows:

1. The test results obtained on the VASCO-X2 (.24 carbon) high hot hardness tool steel gears revealed that this material demonstrated a capability of carrying at least 30 percent more load than gears fabricated from AISI 9310 (AMS 6260) case carburized steel.
2. It is believed that the load carrying capacity of the VASCO-X2 gears may have been affected by the high percentage of retained austenite and heavy carbide network disclosed by the destructive metallurgical examination.
3. An analysis of the ten VASCO-X2 data points and the ten AISI 9310 data points revealed that both materials exhibited a very small degree of scatter, thereby indicating a high degree of repeatability.

FOREWORD

This report presents an evaluation and the results of an experimental program for the investigation of the surface fatigue load capacity of one candidate advanced gear material and one of the current aircraft gear steels. The evaluation was accomplished by conducting rotating load testing of typically sized aircraft quality spur gears manufactured from the two materials. The program was conducted during the period from 24 June 1969 to 28 October 1970 for the U. S. Naval Air Propulsion Test Center, Philadelphia, Pennsylvania under Contract N00156-69-C-0634 (Mod P002).

Technical direction was provided by Mr. James Conboy, Aerospace Engineer of the Naval Air Propulsion Test Center.

The program was conducted at the Vertol Division of the Boeing Company, under the technical supervision of A. J. Lemanski, Chief Advanced Drive System Technology Department. Principal investigators for the program were J. P. Alberti, Project Engineer and V. J. Perillo. Data analysis was accomplished by H. J. Rose.

Acknowledgement is made to Professor W. J. Murphy and his staff at Villanova University for their contributions and assistance during the experimental test program phase.

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
SUMMARY	iii
FOREWORD	v
LIST OF ILLUSTRATIONS	vii
LIST OF TABLES	x
1. INTRODUCTION	1
2. TECHNICAL APPROACH	3
Background	3
Statement of Problem	3
3. TEST METHOD	5
Test Specimen Design	5
Material	15
Specimen Fabrication	15
Metallurgical Evaluation	15
Test Apparatus	18
Testing Technique	18
Gear Stress Calculations	25
4. TEST RESULTS	29
Test Data	29
Discussion	29
Data Analysis	45
5. CONCLUSIONS	53
6. RECOMMENDATIONS	55
7. REFERENCES AND BIBLIOGRAPHY	57

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
	Summary of Mean Endurance Limits	iii
1	AISI 9310 Steel Test Gear for Rotating Fatigue Test (SK21984, 1.67 Gear Ratio, 5.33 Diametral Pitch)	7
2	AISI 9310 Steel Test Pinion for Rotating Fatigue Test (SK21985, 1.67 Gear Ratio, 5.33 Diametral Pitch)	9
3	VASCO-X2 Test Gear for Rotating Fatigue Test (SK21988, 1.67 Gear Ratio, 5.33 Diametral Pitch)	11
4	VASCO-X2 Test Pinion for Rotating Fatigue Test (SK21989, 1.67 Gear Ratio, 5.33 Diametral Pitch)	13
5	Tooth No. 4 of AISI 9310 Steel Test Pinion (SK21985, Serial No. 5, As Received)	16
6	Tooth No. 8 of AISI 9310 Steel Test Gear (SK21984, Serial No. 1, As Received)	16
7	Tooth No. 24 of VASCO-X2 Steel Test Gear (SK21988, Serial No. 1, Side A, As Received)	17
8	Tooth No. 5 of VASCO-X2 Steel Test Pinion (SK21989, Serial No. 1, Side B, As Received)	17
9	Gear Research Test Stand	20
10	Research Test Stand Overhung Configuration	21
11	Deadweight Torsion Test Machine	23
12	Test Box Vibration Signatures for SK21988 (Serial No. 1, Side B) and SK21989 (Serial No. 1) at Scale of 0.05 Volts per Centimeter	24

<u>Figure</u>		<u>Page</u>
13	Test Gear Bending Stress (SK21984, SK21985, SK21988, and SK21989)	26
14	Test Gear Pitch Line Contact Stress (SK21984, SK21985, SK21988, and SK21989)	28
15	Final Condition of AISI 9310 Steel Test Pinion (SK21985, Serial No. 2)	36
16	Final Condition of AISI 9310 Steel Test Pinion (SK21985, Serial No. 3)	37
17	Final Condition of AISI 9310 Steel Test Pinion (SK21985, Serial No. 5)	38
18	Final Condition of AISI 9310 Steel Test Pinion (SK21985, Serial No. 4)	39
19	Final Condition of AISO 9310 Steel Test Pinion (SK21985, Serial No. 1)	40
20	Final Condition of VASCO-X2 Steel Test Pinion (SK21985, Serial No. 4)	41
21	Final Condition of VASCO-X2 Steel Test Pinion (SK21989, Serial No. 3)	42
22	Final Condition of VASCO-X2 Steel Test Pinion (SK21989, Serial No. 2)	43
23	Final Condition of VASCO-X2 Steel Test Pinion (SK21989, Serial No. 5)	44
24	Contact Burn on AISI 9310 Steel Pinion	46
25	Surface Durability Life Factor (AGMA Standard 210.02)	49
26	Test Data Points with Mean Endurance Limits at 99 Percent Confidence Level	50
27	Mean Endurance Limits for a 99.5 Percent Probability of Survival	52

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Test Specimen General Design Parameters . . .	6
2	Specified Chemical Composition (Percentage by Weight)	19
3	Actual Test Specimen Metallurgical Analysis (One Sample of Each Material)	19
4	Load Schedule for Baseline AISI 9310 Steel Gears	30
5	Load Schedule for VASCO-X2 Steel Gears	30
6	Summary of Test Results for AISI 9310 Steel Test Gears (Spur)	31
7	Summary of Test Results for VASCO-X2 Steel Test Gears	33
8	Results of Statistical Analysis	47
9	Test Data and Calculated Endurance Limits . .	48

1. INTRODUCTION

The objective of this project was to investigate the surface load carrying capability of spur test gear specimens fabricated from VASCO-X2 case carburized high hot hardness tool steel as compared to current aircraft baseline test gears fabricated from AISI 9310 steel.

During the past decade, a significant problem in helicopter transmission gearing has been the incidence of pitting failures. Considerable effort has been expended by the aircraft industry in an attempt to find a consistent solution to this problem. To date, these efforts have not provided the desired results.

Elements such as gear teeth which roll and slide against each other under high contact pressures are subjected to the development of surface pits or spalls after many repetitions of load. This pitting is generally understood as a manifestation of metal fatigue due to the imposed cyclic contact stresses.

It is also becoming recognized that one of the principal modes of contact fatigue is initiated by surface distress due to thin oil films, and the majority of slow speed gear drives are operating with only partial elastohydrodynamic separation. Distress of this type is likely to be strongly affected by the interacting chemistry of the steel and fluid.

Steel composition alone is not thought to have a significant effect on pitting fatigue, except insofar as it influences hardenability and microstructure. On the other hand, interactions between different steels or microstructures and lubricants do seem to influence fatigue behavior.

2. TECHNICAL APPROACH

Background

Boeing's Vertol Division has long recognized the need for a more reliable gear material for helicopter transmissions. In 1966 a company-sponsored independent research program was initiated to explore improved materials with a potential of increased load carrying capacity over current gear materials. The initial program was exploratory in nature and consisted of a screening evaluation of several tool steels, nitralloy steels, and carburizing steels. From this work, the VASCO-X2 high hot hardness tool steel was selected for further evaluation.

A follow-on company-sponsored screening program was initiated in 1967 to evaluate the relative surface load carrying capacity of VASCO-X2 (.24 carbon) case carburized steel. The test specimens were spur gears of 5 diametral pitch, 0.50-inch face width and 6.00-inches pitch diameter fabricated to aircraft quality standards. This gear test program revealed the following:

1. The rotating surface fatigue evaluation testing of the VASCO-X2 (.24 carbon) test gears demonstrated the capability of successfully carrying 2.40 times the design load for 10 million cycles without evidence of pitting or spalling. The Hertz contact stress at this load level was 216,000 psi in comparison to 150,000 psi for the design load.
2. There was evidence that the VASCO-X2 test gears developed a protective surface layer on the working tooth surface under the operating loads. The protective layer was evident after an initial period of operation.

Statement of Problem

Current helicopter transmission power gears are limited in load carrying capacity because current materials do not resist surface damage in the form of pitting and spalling failures. However, the bending strength and flexural fatigue resistance of these materials has not imposed design limitations of the same order. In the case of bending stress index allowables, the designer appears to have a considerably greater margin in which to work.

The primary concern of the transmission gear design engineer is in providing adequate tooth strength. For this reason, gear materials are selected mainly for beam strength. To improve the sliding behavior of the material, the usual procedure is to then harden the surfaces. Due to the emphasis on the development of gear materials for strength rather than for good sliding characteristics, most aircraft gears will pit or spall under conditions which are far less severe than those which would cause tooth breakage, particularly at low speeds. In many aircraft gear applications, pitting is a limiting factor in reducing the size and weight of transmissions.

Requirements for the next generation of helicopter and V/STOL transmission designs are placing stringent demands on power gear materials. It has become increasingly obvious that substantial improvements in load capacity and performance cannot be expected from current gear materials. Therefore, aircraft performance will be penalized by reductions in payload because of the increased transmission weights necessary to meet the performance objectives of increased reliability and maintainability.

This problem may be overcome by the use of advanced gear materials that provide greater resistance to surface fatigue failures than present materials, and do not compromise resistance to flexural fatigue failures.

3. TEST METHOD

Test Specimen Design

The design of the test gears used in this program was within the experience range of helicopter main transmission power gears in pitch diameter, diametral pitch, pressure angle and profile modification. Processing procedures, tolerance parameters, and record requirements conformed to the appropriate Boeing-Vertol production specifications. The test gear design parameters were carefully selected to increase the probability of producing pitting failures, while reducing the probability of experiencing scoring (scuffing) and/or bending failures.

With this objective in mind, and to determine the surface load capacity of the two materials under investigation on a comparative basis, the test gears for this program were designed with the following specific parameters. The gear ratio (M_g) of 1.67 to 1.00 was selected as the most practical for a 6.00-inch center distance while maintaining a reasonable bolt circle for mounting purposes. The roll angle to the first point of contact on the pinion member was maintained below 7 degrees. The pinion member was designed with a short addendum (0.06-inch) and the gear member with a long addendum (0.22-inch). The resulting profile contact ratio was 1.13 minimum, which is below normal design practice. Pinion input speed was selected as 910 rpm.

Kinematic analysis of the design parameters, using an existing Boeing-Vertol computer program, indicated a very high specific sliding (slide/roll ratio) value at the first point of contact on the pinion member. The specific sliding value at this point was considerably higher than the value for any other point along the tooth profile, indicating a high probability of experiencing surface type failures in the pinion dedendum.

Each group of test gears (for each of the two materials) was fabricated from one heat and melt of material, and heat treated in one lot (except for one gear member for the VASCO-X2 steel) to minimize possible processing variations. Eleven test gears were manufactured from the AISI 9310 steel and ten gears were manufactured from the VASCO-X2 (.24 carbon) steel in accordance with the drawing specifications shown in Figures 1, 2, 3, and 4. The general design parameters are listed in Table 1.

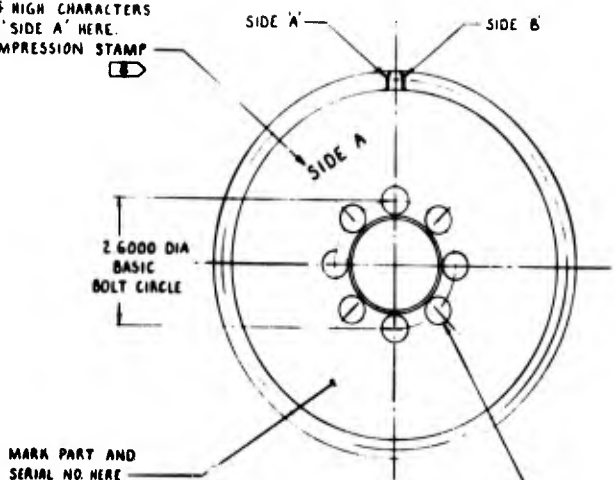
The final design parameters selected for the gear test specimens were specifically chosen to increase the pitting probability; consequently, they are not representative of typical aircraft design practice.

TABLE 1. TEST SPECIMEN GENERAL DESIGN PARAMETERS

Drawing Number	Description	Material (Steel)	Pitch Diameter (inches)	Diametral Pitch	Gear Ratio	Pressure Angle (degrees)	Face Width (inches)
SK21984	Gear	AISI 9310	7.500	5.333	1.67	20	0.500
SK21985	Pinion	AISI 9310	4.500	5.333	1.67	20	0.500
SK21988	Gear	VASCO-X2	7.500	5.333	1.67	20	0.500
SK21989	Pinion	VASCO-X2	4.500	5.333	1.67	20	0.500

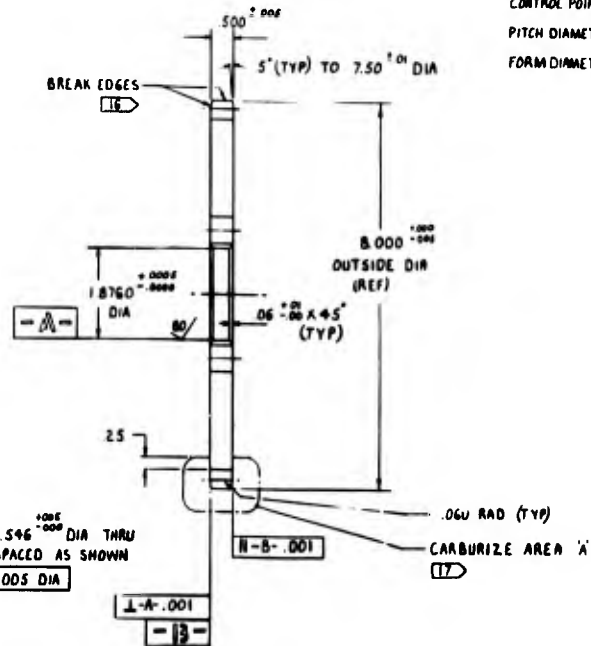
REFERENCE DATA			
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	3.05 MAX	3.087 MIN	NUM DIA
BACKLASH WITH MATING GEAR ON STANDARD CENTERS	0.12 MAX	0.08 MIN	PRES PITCH
BASE CIRCLE DIAMETER (REF)	7.0476952		OUT ROD
LEAD TOLERANCE PER INCH OF FACE WIDTH			
A .0001	RH	B .0001	RH FOR MEAS
.0001	LH	.0001	LH FULL FIN
TOTAL INDEX TOLERANCE			
A .0006	B .0006		
PITCH TOLERANCE			
A .0002	B .0002		

MARK IN $\frac{1}{4}$ HIGH CHARACTERS THE WORD 'SIDE A' HERE. DO NOT IMPRESSION STAMP



MARK PART AND SERIAL NO. HERE

8 HOLES .546^{+0.005} DIA THRU EQUALLY SPACED AS SHOWN
 $\frac{80}{\phi .005 \text{ DIA}}$

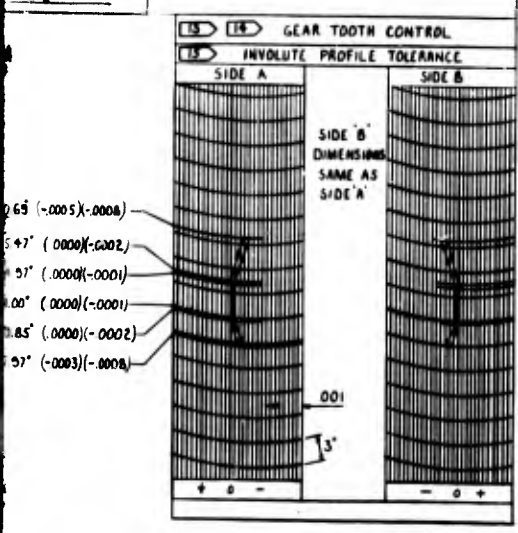


- OUTSIDE DIAMETER 5.000 (-.0005)(+.0008)
- CONTROL POINT NO.1 2.547" (.0000)(-.0002)
- CONTROL POINT NO.2 2.497" (.0000)(-.0001)
- CONTROL POINT NO.3 21.00" (.0000)(-.0001)
- PITCH DIAMETER 20.85" (.0000)(-.0002)
- FORM DIAMETER 17.97" (-.0003)(-.0008)

Figure 1. AISI 9310 Steel Test Gear for Rotating Fatigue Test (SK21984, 1.67 Gear Ratio, 5.33 Diametral Pitch)

A

EXTERNAL SPUR GEAR DATA			
TA			
3105 MAX	NUMBER OF TEETH		40
5087 MIN	DIAMETRAL PITCH		5.3333
012 MAX	PRESSURE ANGLE		20
008 MIN	PITCH DIAMETER @ A-.001 TIR		7.500
70476952	OUTSIDE DIAMETER		8.000 ±.002
OF FACE WIDTH	ROOT DIAMETER		7.213 ±.002
0001 RH	FORM DIAMETER		7.3861
0001 LH	MEASUREMENT OVER TWO PINS		8.1586 MAX 8.1395 MIN
ANCE.	FULL FILLET RADIUS (REF)		.126
0006	PIN DIAMETER		.3840
0002			



NOTES

- 1 ALL DIAMETERS ON A COMMON CENTERLINE TO BE CONCENTRIC TO EACH OTHER WITHIN .010 TIR, UNLESS OTHERWISE NOTED.
- 2 MAXIMUM SURFACE ROUGHNESS $125/\sqrt{\text{R}}$ EXCEPT AS NOTED.
- 3 RELATIVE AZIMUTH POSITION OF GEAR TEETH AND HOLES OPTIONAL UNLESS SPECIFIED.
- 4 BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER OF .010 TO .020
- 5 NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436.
- 6 FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5424 CLASS A.
- 7 FINISH ON GEAR TEETH FLANKS $33/\sqrt{\text{R}}$ MAXIMUM BOTH SIDES.
- 8 MARK PART AND SERIAL NUMBER HERE. VIBRO ETCH PER BOEING PROCESS SPECIFICATION BAC 5307 TYPE 'VE'. DO NOT IMPRESSION STAMP.
- 9 LEAD TOLERANCE APPLIES TO FULL FACE WIDTH MINUS EDGE BREAKS. CROWNING OR END RELIEF TO BE AVOIDED.
- 10 BILLET OR BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTION OF 3 TO 1 FROM THE INGOT.
- 11 CARBURIZED TEST SAMPLES SHALL BE FACSIMILES OF GEAR TEETH.
- 12 QUALITY CONTROL PER BOEING SPECIFICATION MS 14.02
- 13 PROFILE SHAPE WITHIN THE TOLERANCE BAND SHALL BE A SMOOTH AND GRADUAL CONVEX CURVATURE. NO STEPS OR GROOVES PERMITTED.
- 14 THE FULL CIRCULAR FILLET SHALL BE A SMOOTH CURVATURE WITH NO STEPS OR GROOVES.
- 15 THE TOOTH PROFILES AND FILLETS SHALL BE FINISH MACHINED BY FORM GRINDING WITH NO UNDERCUT PERMITTED.
- 16 BREAK ALL EDGES OF GEAR TEETH .005 TO .015 WITH TAMPCO BRUSH.
- 17 HEAT TREATMENT

A. CARBURIZE ENCLOSED AREAS PER BOEING PROCESS SPECIFICATION MS 12.02	AREA A	AREA B
B. CARBURIZED CASE HARDNESS ROCKWELL C	60-64	
C. EFFECTIVE CASE DEPTH AFTER GRINDING	0.30-0.45	
D. CORE HARDNESS ROCKWELL C	36-40	
E. CORE STRENGTH PSI (REF)	160,000	
F. DRAW AT 300°F TO 325°F FOR FOUR HOURS AFTER FINAL GRIND.	181,000	

B

REFERENCE DATA					
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.2702 MAX .2683 MIN				
BACKLASH WITH MATING GEAR ON STANDARD CENTERS	.012 MAX .008 MIN				
BASE CIRCLE DIAMETER (REF)	4.2286167				
LEAD TOLERANCE PER INCH OF WIDTH					
A	.0001	RH	B	.0001	RH
	.0001	LH		.0001	LH
TOTAL INDEX TOLERANCE					
A	.0006		B	.0006	
PITCH TOLERANCE					
A	.0002		B	.0002	

OUTSIDE DIAMETER	2.505	(-.0007)(-.0010)
PITCH DIAMETER	2.085	(.0000)(-.0002)
CONTROL POINT NO1	19.76	(.0000)(.0001)
CONTROL POINT NO2	10.76	(.0000)(-.0001)
FORM DIAMETER	1.76	(-.0006)(-.0009)

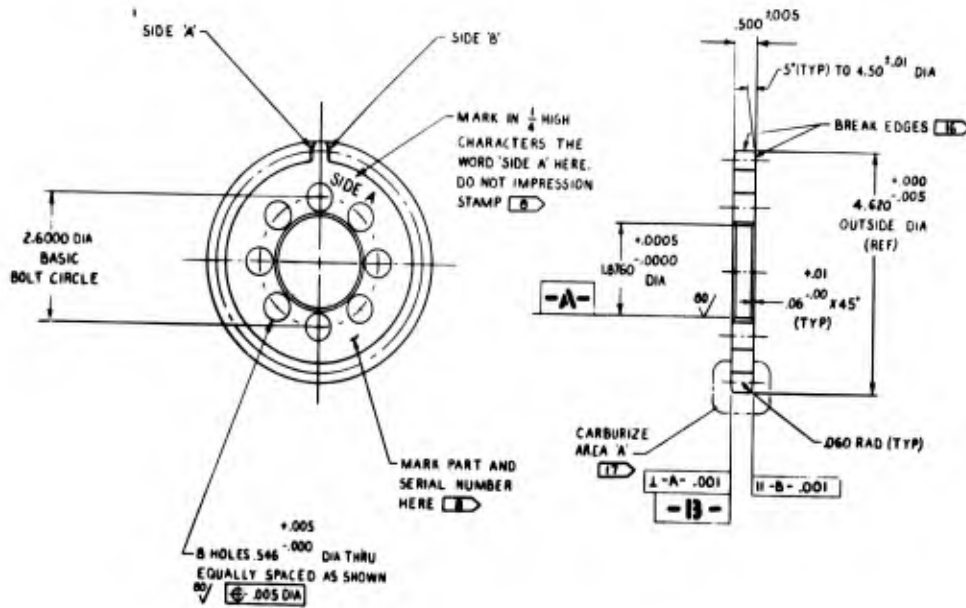


Figure 2. AISI 9310 Steel Test Pinion for Rotating Fatigue Test (SK21985, 1.67 Gear Ratio, 5.33 Diametral Pitch)

A

REFERENCE DATA			
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.3103 MAX	.3087 MIN	NUMB
BACKLASH WITH MATING GEAR ON STANDARD CENTERS	.012 MAX	.008 MIN	DIAM
BASE CIRCLE DIAMETER (REF)	7.0476332		PRESS
LEAD TOLERANCE PER INCH OF FACE WIDTH	A .0001 RH B .0001 RH		OUTS
	A .0001 LH B .0001 LH		ROOT
TOTAL INDEX TOLERANCE	A .0006 B .0006		FORM
	A .0002 B .0002		MEAS
PITCH TOLERANCE	A .0002 B .0002		FULL
	A .0002 B .0002		PIN D

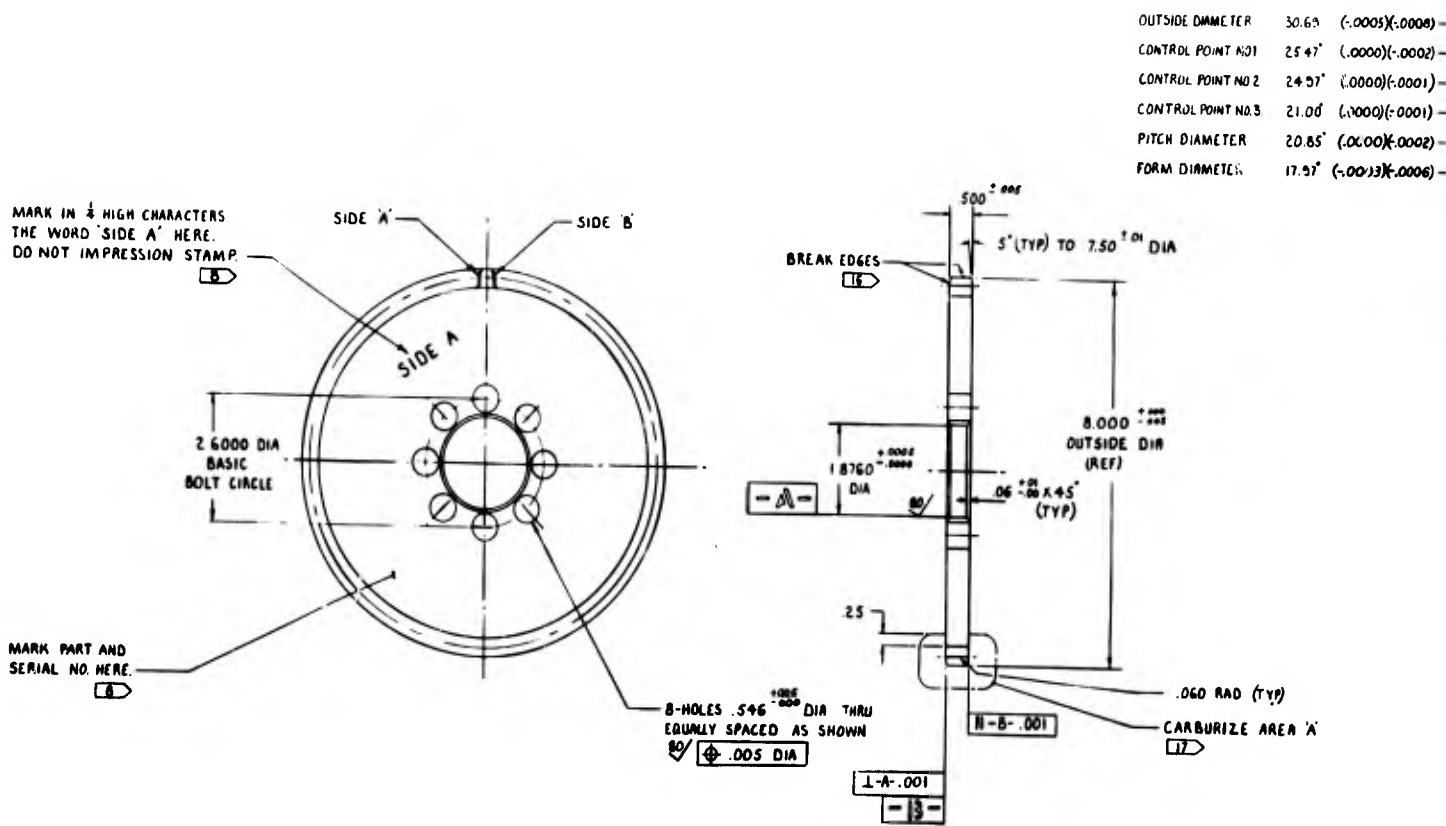
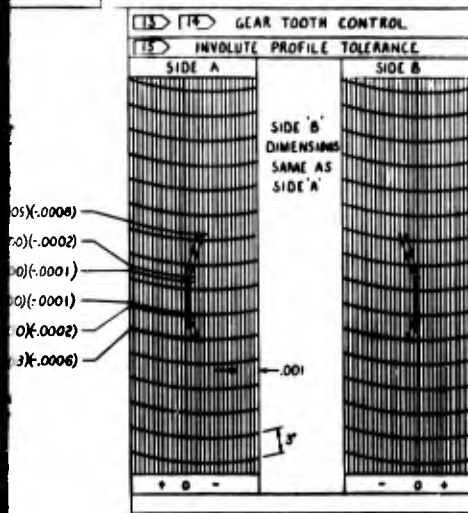


Figure 3. VASCO-X2 Test Gear for Rotating Fatigue Test (SK21988, (SK21988, 1.67 Gear Ratio, 5.33 Diametral Pitch)

A

EXTERNAL SPUR GEAR DATA		
05 MAX	NUMBER OF TEETH	40
087 MIN	DIAMETRAL PITCH	5.3333
02 MAX	PRESSURE ANGLE	20
08 MIN	PITCH DIAMETER (B-A-.001 TIR)	7.500
07652	OUTSIDE DIAMETER	8.000 ±.002
WIDTH	ROOT DIAMETER	7.213 ±.002
RH	FORM DIAMETER	7.3861
LH	MEASUREMENT OVER TWO PINS	8.196 MAX 8.132 MIN
	FULL FILLET RADIUS (REF)	.126
	PIN DIAMETER	.3840



NOTES

- ALL DIAMETERS ON A COMMON CENTERLINE TO BE CONCENTRIC TO EACH OTHER WITHIN .010 TIR. UNLESS OTHERWISE NOTED.
- MAXIMUM SURFACE ROUGHNESS $\sqrt{15}$ EXCEPT AS NOTED.
- RELATIVE AZIMUTH POSITION OF GEAR TEETH AND HOLES OPTIONAL UNLESS SPECIFIED.
- BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER OF .010 TO .020
- NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436.
- FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5424 CLASS A.
- FINISH ON GEAR TEETH FLANKS $\sqrt{15}$ MAXIMUM BOTH SIDES.
- MARK PART AND SERIAL NUMBER HERE. VIBRO ETCH PER BOEING PROCESS SPECIFICATION BAC 5307 TYPE 'VE'. DO NOT IMPRESSION STAMP.
- LEAD TOLERANCE APPLIES TO FULL FACE WIDTH MINUS EDGE BREAKS. CROWNING OR END RELIEF TO BE AVOIDED.
- BILLET OR BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTION OF 3 TO 1 FROM THE INGOT.
- CARBURIZED TEST SAMPLES SHALL BE FACSIMILES OF GEAR TEETH.
- QUALITY CONTROL PER BOEING SPECIFICATION MS 14.02
- PROFILE SHAPE WITHIN THE TOLERANCE BAND SHALL BE A SMOOTH AND GRADUAL CONVEX CURVATURE. NO STEPS OR GROOVES PERMITTED.
- THE FULL CIRCULAR FILLET SHALL BE A SMOOTH CURVATURE WITH NO STEPS OR GROOVES.
- THE TOOTH PROFILES AND FILLETS SHALL BE FINISH MACHINED BY FORM GRINDING WITH NO UNDERCUT PERMITTED.
- BREAK ALL EDGES OF GEAR TEETH .005 TO .015 WITH TAMPCO BRUSH.
- PURCHASE MATERIAL FROM:-
VANADIUM ALLOYS STEEL COMPANY LATROBE, PENNSYLVANIA.
VASCO LOW CARBON HOT FORM. APPROXIMATE ANALYSIS:

CARBON	2.4	SULPHUR	.007	MOLYBDENUM	1.32
SILICON	.83	PHOSPHORUS	.009	VANADIUM	.47
MANGANESE	.30	CHROMIUM	4.700	TUNGSTEN	1.41
- HEAT TREATMENT
 - ANNEAL
 - 1600-1650°F ONE HOUR
 - COOL TO 800°F AT 50 DEGREES F PER HOUR.
 - AIR COOL TO ROOM TEMPERATURE.
 - ROUGH MACHINE.
 - STABILIZE HEAT TREAT.
 - COPPER PLATE TO BAC 5722 AND PREHEAT 1400°F IN PROTECTIVE ATMOSPHERE.
 - HARDEN 1850°F IN PROTECTIVE ATMOSPHERE.
 - AIR QUENCH TO ROOM TEMPERATURE.
 - DOUBLE TEMPER 2-4 HOURS AT 1200°F FOR ROCKWELL 36 NOMINAL.
 - FINISH MACHINE EXCEPT FINAL GRIND.
 - CARBURIZE:
 - ALUMINUM OXIDE CLEAN.
 - PREHEAT 1750°F ONE HOUR.
 - CARBURIZE AT 1750°F WITH .90-.95 PERCENT CARBON CONTENT IN OUTER .005 OF CASE TO ACHIEVE AN EFFECTIVE CASE DEPTH (ROCKWELL C50) AFTER GRINDING .030-.045 INCHES.(REF NOTE 18.7)
 - STILL AIR QUENCH TO 125-150°F.
 - DOUBLE TEMPER 950°F 2-4 HOURS.
 - FINISH GRIND AS REQUIRED.
 - CARBURIZE ENCLOSED AREA 'A'. CONTROL OF CARBURIZING PROCESS SHALL BE TO MS 12.02
 CARBURIZED CASE HARDNESS ROCKWELL C — 60-64
 EFFECTIVE CASE DEPTH AFTER GRINDING — .030-.045
 CORE HARDNESS ROCKWELL C — 50 MAX
 B ALL CARBURIZING AND HEAT TREATMENT EQUIPMENT SHALL CONFORM TO MIL-N-6875.

B

REFERENCE DATA				
CIRCULAR TOOTH THICKNESS AT PITCH DIAMETER	.2702 MAX .2683 MIN			
BACKLASH WITH MATING GEAR ON STANDARD CENTERS	.012 MAX .008 MIN			
BASE CIRCLE DIAMETER (REF)	4.2286167			
LEAD TOLERANCE PER INCH OF WIDTH				
A	.0001	RH	B	.0001
		LH		.0001
TOTAL INDEX TOLERANCE				
A	.0006		B	.0006
PITCH TOLERANCE				
A	.0002		B	.0002

OUTSIDE DIAMETER	25.05	(-.0007)(-.0010)
PITCH DIAMETER	20.85	(-.0000)(-.0002)
CONTROL POINT NO 1	19.76	(.0000)(.0001)
CONTROL POINT NO 2	10.76	(.0000)(-.0001)
FORM DIAMETER	1.76	(.0006)(-.0009)

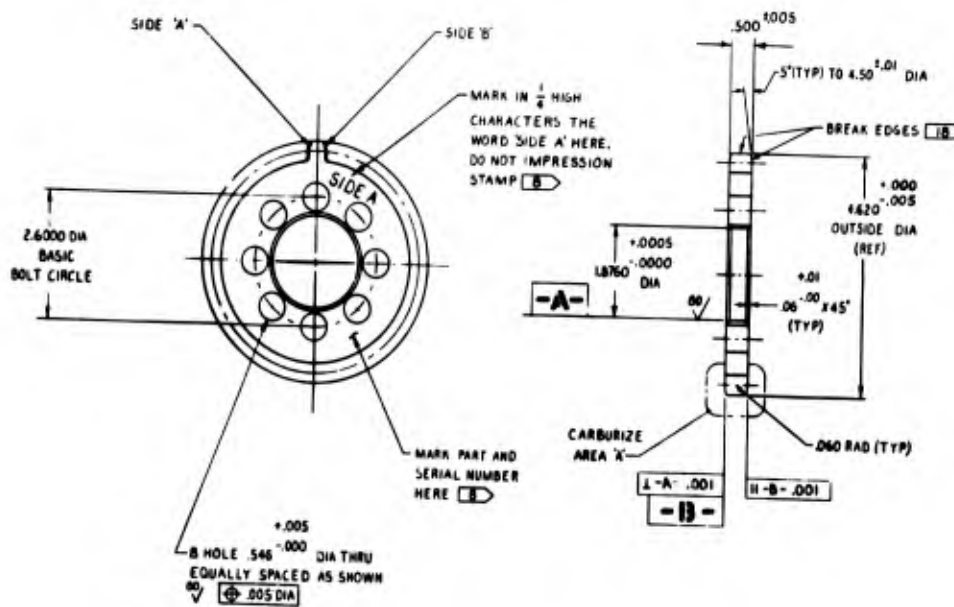
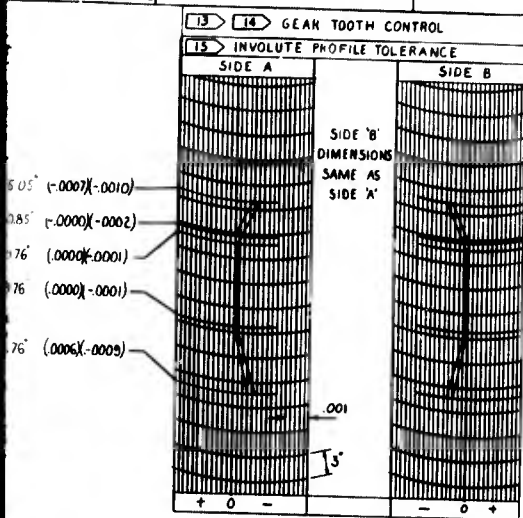


Figure 4. VASCO-X2 Test Pinion for Rotating Fatigue Test
(SK21989, 1.67 Gear Ratio, 5.33 Diametral Pitch)

A

EXTERNAL SPUR GEAR DATA			
AT	.2702 MAX .2683 MIN	NUMBER OF TEETH DIAMETRAL PITCH	24 5.3333
ON	.012 MAX .008 MIN	PRESSURE ANGLE PITCH DIAMETER	20° 4.5000
	4.2286167	OUTSIDE DIAMETER	4.620 ^{+0.005} _{-0.005}
INCH OF WIDTH		ROOT DIAMETER	4.005 ^{+0.005} _{-0.005}
B .0001 RH .0001 LH		FORM DIAMETER	4.2306
LERANCE		MEASUREMENT OVER TWO PINS	3.8978 MAX 3.8923 MIN
B .0006		FULL FILLET RADIUS (REF)	.120
NCE		PIN DIAMETER	.3840
B .0002			



NOTES

1. ALL DIAMETERS ON A COMMON CENTERLINE TO BE CONCENTRIC TO EACH OTHER WITHIN .010 T.I.R. UNLESS OTHERWISE NOTED.
2. MAXIMUM SURFACE ROUGHNESS \sqrt{R} EXCEPT AS NOTED.
3. RELATIVE AZIMUTH POSITION OF GEAR TEETH AND HOLES OPTIONAL UNLESS SPECIFIED.
4. BREAK ALL SHARP EDGES NOT SPECIFIED TO A RADIUS OR CHAMFER OF .010 TO .020
5. NITAL ETCH INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5436
6. FLUORESCENT MAGNETIC PARTICLE INSPECTION PER BOEING PROCESS SPECIFICATION BAC 5424 CLASS A.
7. FINISH ON GEAR TEETH FLANKS \sqrt{R} MAXIMUM BOTH SIDES.
8. MARK PART AND SERIAL NUMBER HERE. VIBRO ETCH PER BOEING PROCESS SPECIFICATION BAC 5307 TYPE 'VE'. DO NOT IMPRESSION STAMP.
9. LEAD TOLERANCE APPLIED TO FULL FACE WIDTH MINUS EDGE BREAKS.
10. BILLET OR BAR SHALL HAVE A MINIMUM MECHANICAL REDUCTION OF 3 TO 1 FROM THE INGOT.
11. CARBURIZED TEST SAMPLES SHALL BE FACSIMILES OF GEAR TEETH.
12. QUALITY CONTROL PER BOEING SPECIFICATION MS 14.02
13. PROFILE SHAPE WITHIN THE TOLERANCE BAND SHALL BE A SMOOTH AND GRADUAL CONVEX CURVATURE. NO STEPS OR GROOVES PERMITTED.
14. THE FULL CIRCULAR FILLET SHALL BE A SMOOTH CURVATURE WITH NO STEPS OR GROOVES.
15. THE TOOTH PROFILES AND FILLETS SHALL BE FINISH MACHINED BY FORM GRINDING WITH NO UNDERCUT PERMITTED.
16. PURCHASE MATERIAL FROM:
VANADIUM ALLOYS STEEL COMPANY, LATROBE, PENNSYLVANIA.
VASCO LOW CARBON HOT FORM. APPROXIMATE ANALYSIS:

CARBON	.24	SULPHUR	.007	MOLYBDENUM	1.32
SILICON	.83	PHOSPHORUS	.009	VANADIUM	.47
MANGANESE	.30	CHROMIUM	4.700	TUNGSTEN	1.41
17. HEAT TREATMENT
 1. ANNEAL
 - A. 1600-1650° ONE HOUR
 - B. COOL TO 800° F AT 50 DEGREES F PER HOUR
 - C. AIR COOL TO ROOM TEMPERATURE
 2. ROUGH MACHINE
 3. STABILIZE HEAT TREAT
 - A. COPPER PLATE TO BAC 5722 AND PREHEAT 400° F IN PROTECTIVE ATMOSPHERE.
 - B. HARDEN 1850° F IN PROTECTIVE ATMOSPHERE.
 - C. AIR QUENCH TO ROOM TEMPERATURE.
 - D. DOUBLE TEMPER 2-4 HOURS AT 1200° F FOR ROCKWELL 36 NOMINAL.
 4. FINISH MACHINE EXCEPT FINAL GRIND.
 5. CARBURIZE:
 - A. ALUMINUM OXIDE CLEAN.
 - B. PREHEAT 1750° F ONE HOUR.
 - C. CARBURIZE AT 1750° F WITH .90-.95 PERCENT CARBON CONTENT IN OUTER .005 OF CASE TO ACHIEVE AN EFFECTIVE CASE DEPTH (ROCKWELL C 50) AFTER GRINDING .030-.045 INCHES (REF. NOTE 17.7)
 - D. STILL AIR QUENCH TO 125-150° F.
 - E. DOUBLE TEMPER 950° F 2-4 HOURS.
 6. FINISH GRIND AS REQUIRED.
 7. CARBURIZE ENCLOSED AREA X CONTROL OF CARBURIZING PROCESS SHALL BE TO MS 12.02.

CARBURIZED CASE HARDNESS ROCKWELL C	60-64
EFFECTIVE CASE DEPTH AFTER GRINDING	.030-.045
CORE HARDNESS ROCKWELL C	50 MAX
18. ALL CARBURIZING AND HEAT TREATMENT EQUIPMENT SHALL CONFORM TO MIL-H-6875.
19. BREAK ALL EDGES OF GEAR TEETH .005 TO .015 WITH TAMPICO BRUSH.

B

Material

The two materials selected for this investigation were AISI 9310 (AMS6260) steel and VASCO-X2 (.24 carbon) steel. These two materials are the same as the two candidate materials investigated under a previous contract, N00156-69-C-0634, Evaluation of Advanced Gear Materials for Gear Boxes and Transmissions. The previous program consisted of single-tooth nonrotating testing to evaluate the bending fatigue strength of these two materials. The current program was a logical follow-on to the original program to improve and extend the evaluation of these two materials - by evaluating the surface load carrying capacity through a rotating load test program.

Specimen Fabrication

The test gears for this program were fabricated by a vendor approved for the manufacture of helicopter gears, in accordance with the engineering drawings and the appropriate Boeing-Vertol specifications. The manufacturing procedure for all test gears was similar, and used the following basic processing sequence:

1. Forge material to individual biscuit.
2. Rough machine gear blank and stress relieve.
3. Final machine gear blank (bore, faces, outside diameter).
4. Machine gear teeth (hob).
5. Carburize gear teeth.
6. Heat treat (harden and draw).
7. Finish grind bore and end faces.
8. Grind gear teeth (form ground).
9. Bake.
10. Final inspection.

Figures 5 through 8 are photographs of the test gears in the as received condition.

Metallurgical Evaluation

A destructive metallurgical examination was conducted on SK21985, Serial No. 7, AISI 9310 (AMS6260) steel gear for determination of conformance to Boeing-Vertol specifications. The subject test gear conformed to all requirements and related specifications.

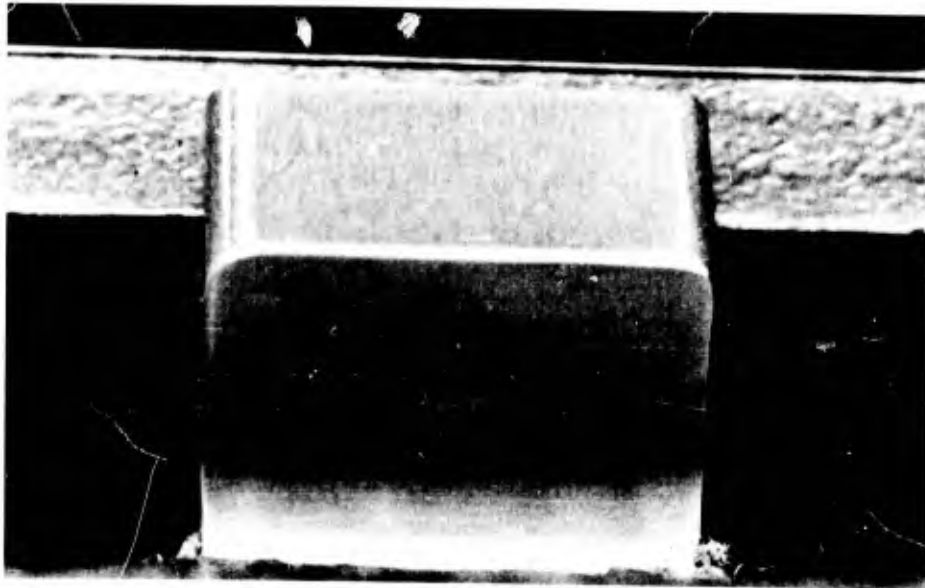


Figure 5. Tooth No. 4 of AISI 9310 Steel Test Pinion (SK21985, Serial No. 5, as received)

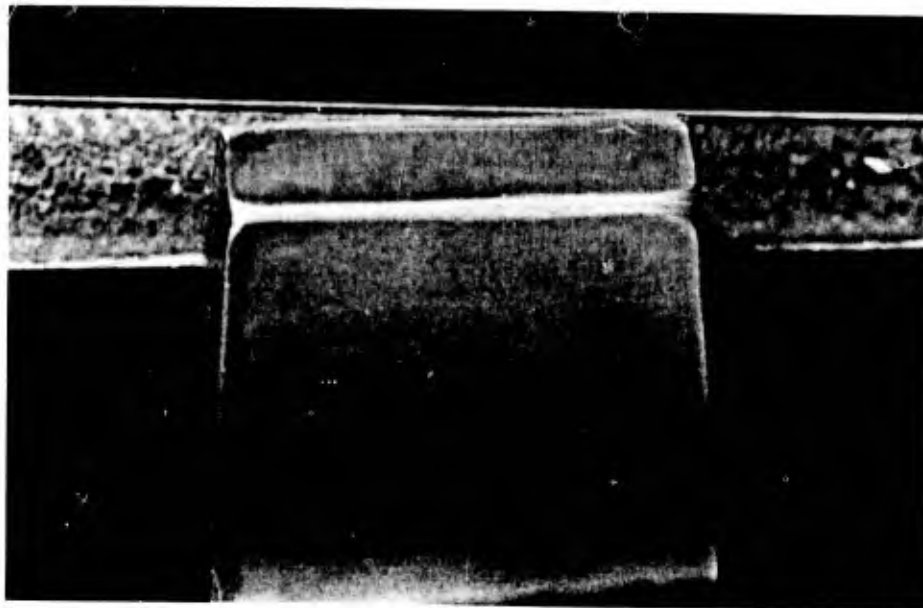


Figure 6. Tooth No. 8 of AISI 9310 Steel Test Gear (SK21984, Serial No. 1, as received)

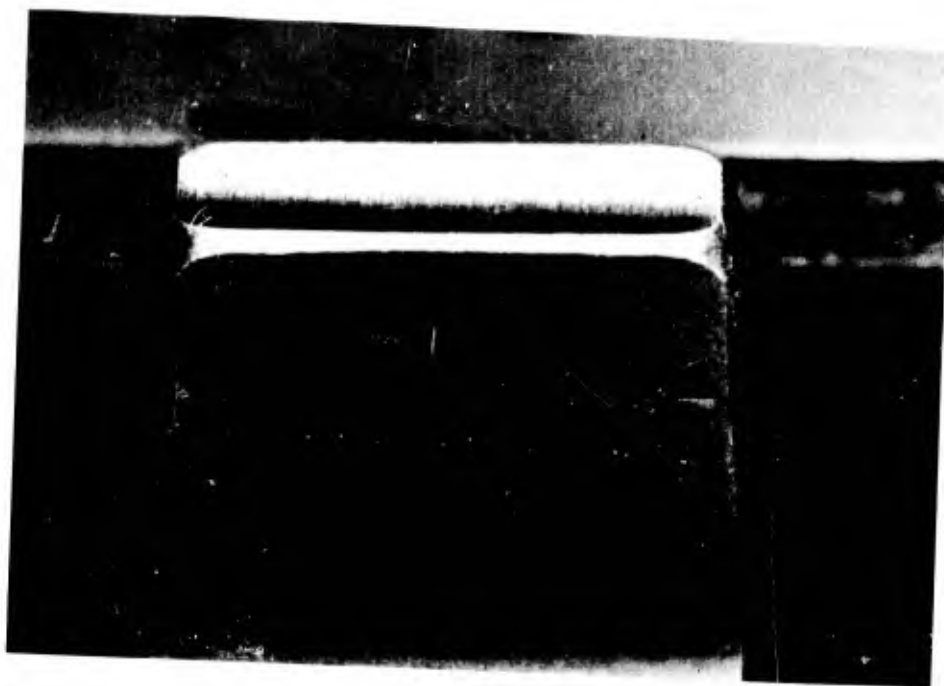


Figure 7. Tooth No. 24 of VASCO-X2 Steel Test Gear (SK21988, Serial No. 1, Side A, as received)

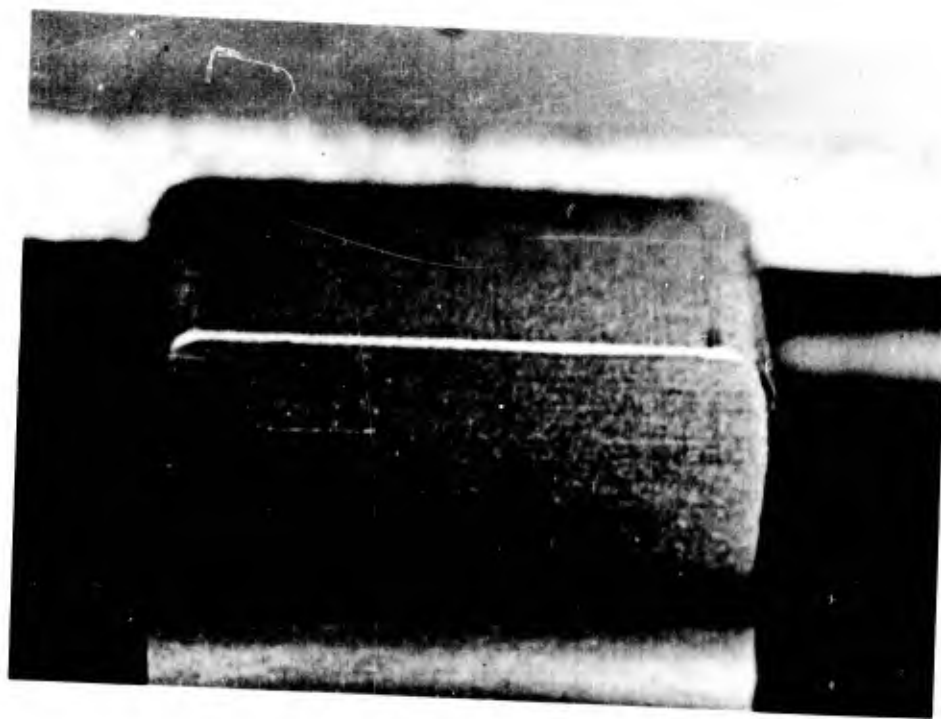


Figure 8. Tooth No. 5 of VASCO-X2 Steel Test Pinion (SK21989, Serial No. 1, Side B, as received)

A destructive metallurgical examination was conducted on SK21989, Serial No. 1, VASCO-X2 steel gear, at the completion of testing, for determination of conformance to Boeing-Vertol specifications. Results of this investigation revealed that the core hardness was RC 53, which is over the requirement of RC 50 maximum. Microscopic examination revealed a heavy network of carbides to a depth of approximately 0.015 inch. This same zone was characterized by nearly circular zones of what appeared to be retained austenite. Microhardness results were above RC 60 at and close to the surface. The core microstructure was uniform tempered martensite. The amount of retained austenite was found to be variable, based on initial examination. Microscopic determinations were made and found to be approximately 30 percent; X-ray surface values were below 10 percent.

Table 2 contains a listing of the specified chemical analysis for the test gear materials and Table 3 lists the actual composition, hardness and cleanliness rating. Except for one gear member of the VASCO-X2 steel, all test gears of the same material were fabricated from the same heat and melt of steel to minimize possible variations which may be introduced by material processing.

Test Apparatus

The gear specimens were tested on a Boeing-Vertol regenerative (four square) load test stand (ST 0150). This test stand was specifically designed and constructed to conduct rotating load test programs for gear research and development. The test machine is capable of operation with three center distance options and provisions for control of torque, oil temperature and quantity of oil. Lubrication of all gear meshes and bearings is provided by individual oil jets (see Figure 9).

To facilitate short term operation and/or surface durability type testing, the design of this test stand includes the provision for testing outboard of the main gear housing, as shown in Figure 10. This feature provides for rapid assembly and disassembly of the test specimens, with improved accessibility for frequent visual inspection. This test stand configuration has a separate lubrication system with heating and cooling capabilities and direct oil flow measurement. Lubrication is directed to the test gears by individual externally cooled oil jets, which can be directed on the in-mesh side, out-of-mesh side, or both sides simultaneously. This configuration also permits control of oil flow rate, oil inlet temperature, and operating torque, while maintaining a constant speed.

Testing Technique

The primary test variables were shaft torque and oil inlet temperature. Gear tooth load was a function of shaft torque, which was applied through a lever system at the beginning of

TABLE 2. SPECIFIED CHEMICAL COMPOSITION
(PERCENTAGE BY WEIGHT)

Element	Symbol	AISI 9310 (AMS6260)	VASCO-X2 (.24 Carbon)
Carbon	C	0.07-0.13	0.20-0.25
Manganese	Mn	0.40-0.70	0.20-0.40
Silicon	Si	0.20-0.35	0.80-1.00
Chromium	Cr	1.00-1.40	4.75-5.25
Molybdenum	Mo	0.08-0.15	1.30-1.50
Vanadium	V	-	0.40-0.50
Tungsten	W	-	1.20-1.50
Nickel	Ni	3.00-3.50	-
Sulphur	S	0.025 Max	0.025 Max
Copper	Cu	0.35 Max	-

TABLE 3. ACTUAL TEST SPECIMEN METALLURGICAL ANALYSIS
(ONE SAMPLE OF EACH MATERIAL)

Specification	AISI 9310 (AMS6260) (%)	VASCO-X2 (.24 Carbon) (%)
Element		
Carbon	0.13	0.26
Manganese	0.60	0.22
Silicon	0.23	1.04
Chromium	1.28	5.30
Molybdenum	0.11	1.28
Vanadium	-	0.44
Tungsten	-	1.25
Nickel	2.99	-
Case Hardness, Rc	60-61	60-62
Core Hardness, Rc	39	53
Grain Size		7

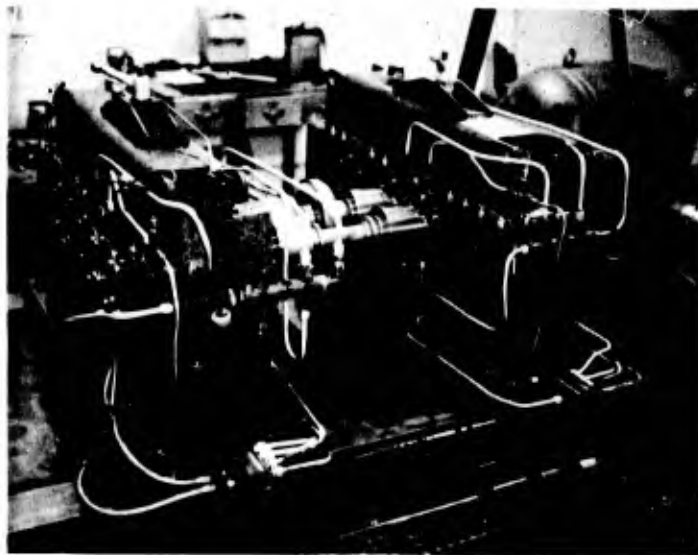
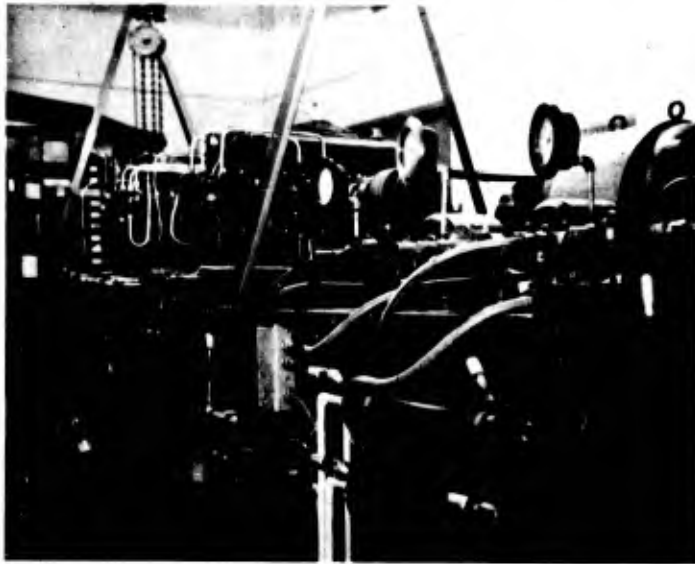


Figure 9. Gear Research Test Stand

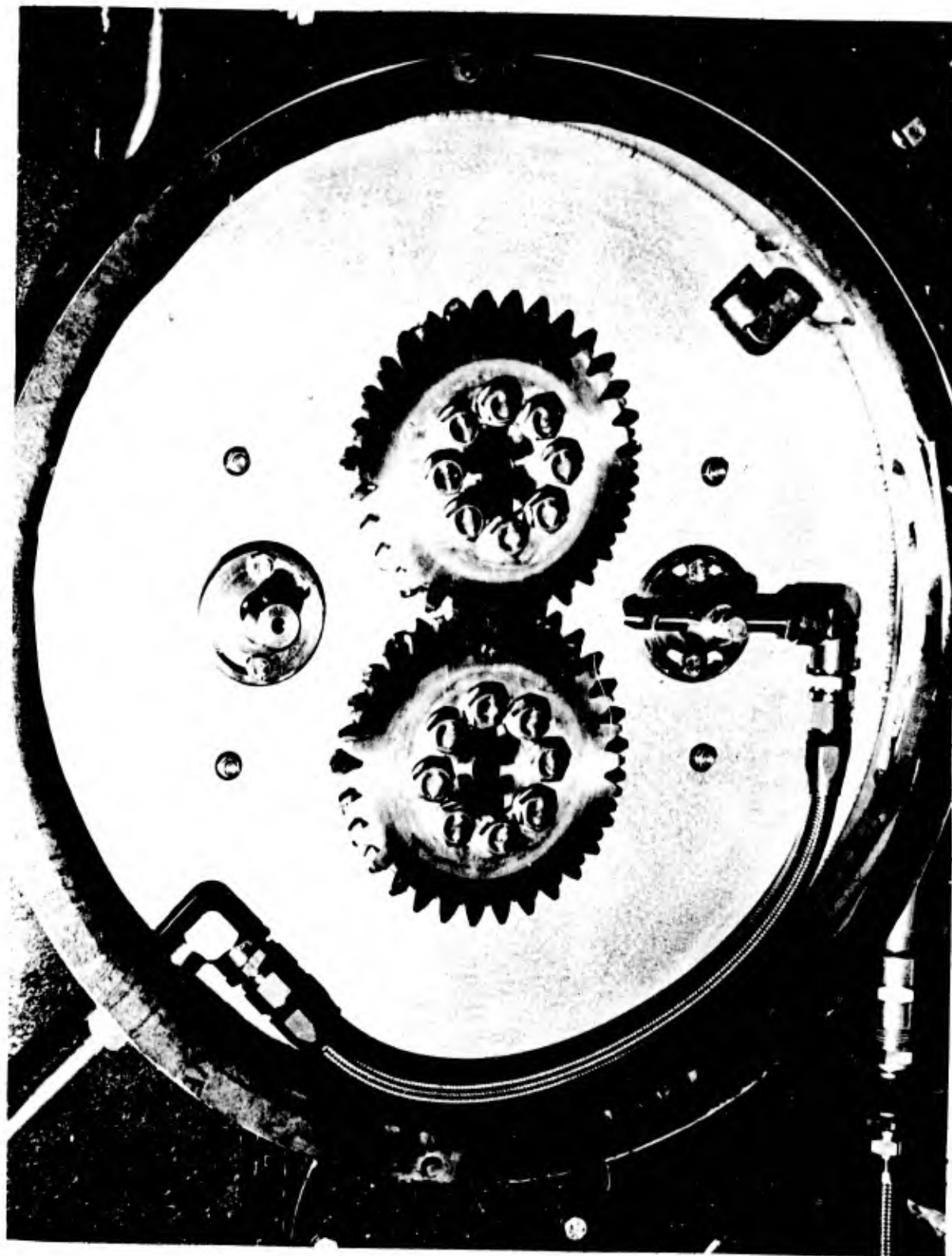


Figure 10. Research Test Stand Overhung Configuration

each test run. Torque levels were observed on an SR2 Strainert instrument at specified intervals, and recorded. A final torque reading was taken and recorded at the conclusion of each test run. Deviation from the initial target torque was controlled to plus or minus 5 percent at startup and within plus or minus 2 percent during the individual test runs.

The torquemeter was calibrated prior to and at the completion of the test program. Calibration of the torquemeter was accomplished on a Riehle deadweight torsion test machine (Figure 11). Recalibration curves agreed within 2 percent with the initial calibration. Test time (cycles) was determined by a log record of running time and an elapsed time meter located in the test stand console. Power was supplied by an electric motor driving the input shaft through a toothed belt arrangement, maintaining the input pinion speed at 910 rpm.

Input oil temperature for the test gearbox was maintained at $135^{\circ}\text{F} + 5^{\circ}$ with input oil pressure of $55 \text{ psi} + 5$. The oil used for lubricating the test gearbox was MIL-L-23699A. Testing technique for this test program consisted of rotating load tests at each of the specified load levels for a maximum of 3 million cycles (or failure). Successful completion of a particular test run for 3 million cycles was considered as a test runout data point. This runout was then considered to be below the fatigue endurance limit. Prior to conducting the test runs the test gearbox oil sump was heated to raise the oil inlet temperature to $135 \text{ degrees} + 5$. The lubricating oil was circulated until the oil-temperature out gave indications of stabilizing. Jet lubrication was provided on the out-of-mesh side for the test gear mesh.

In addition to the visual inspections conducted at the specified intervals, constant surveillance of the test gearbox was provided through the use of accelerometers attached to the gear case. The vibration signatures were observed with an oscilloscope and the amplitudes were recorded in the test program log. Actual vibration signatures were photographed at specified intervals; Figure 12 is a typical example.

The test procedure for all test gears in this program was the same, and consisted of the following sequence.

1. Conduct static pattern checks at the 50 percent and 100 percent load levels for load distribution evaluation.
2. Conduct a run-in rotating load test at the 50 percent load level for one hour (54,600 cycles).

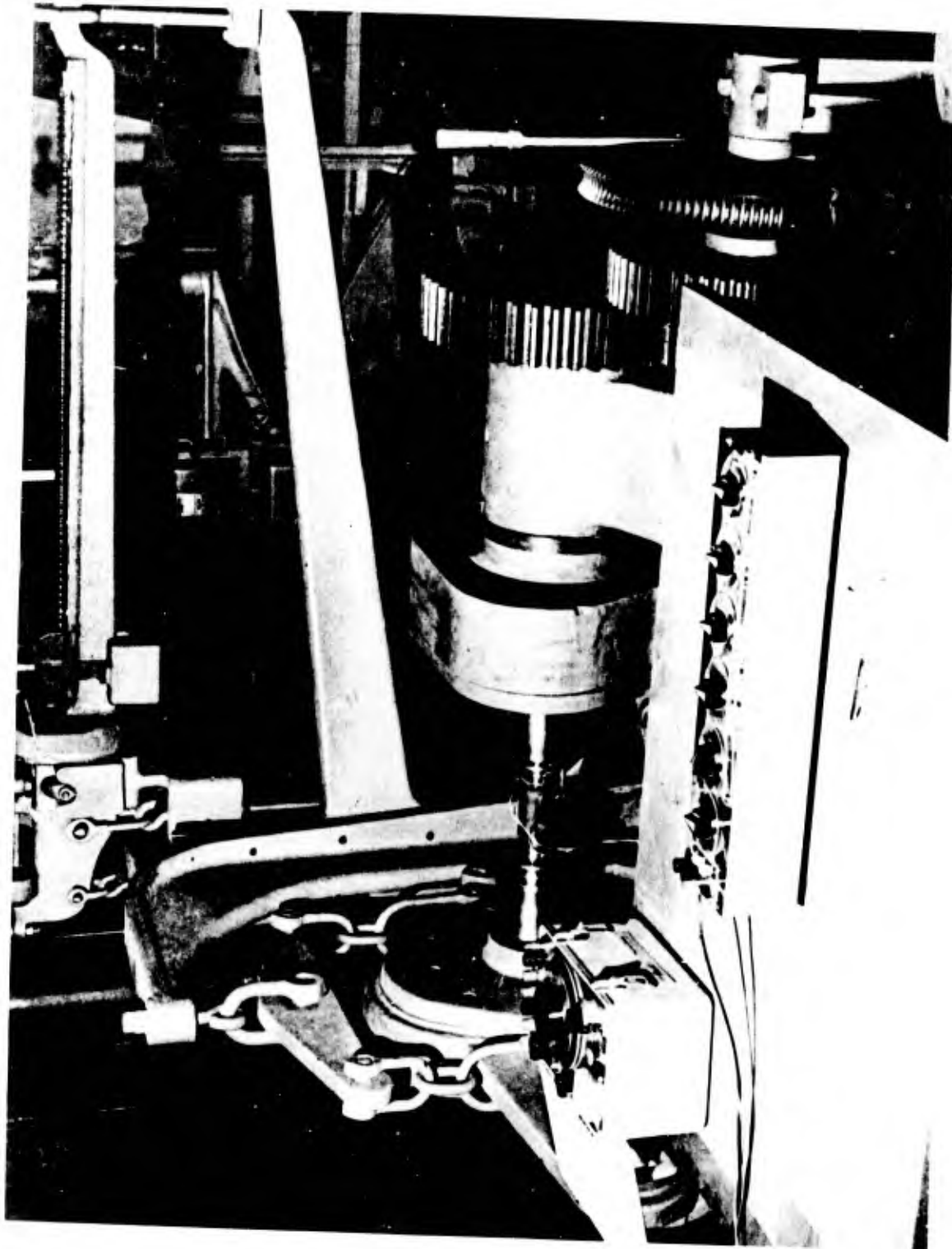
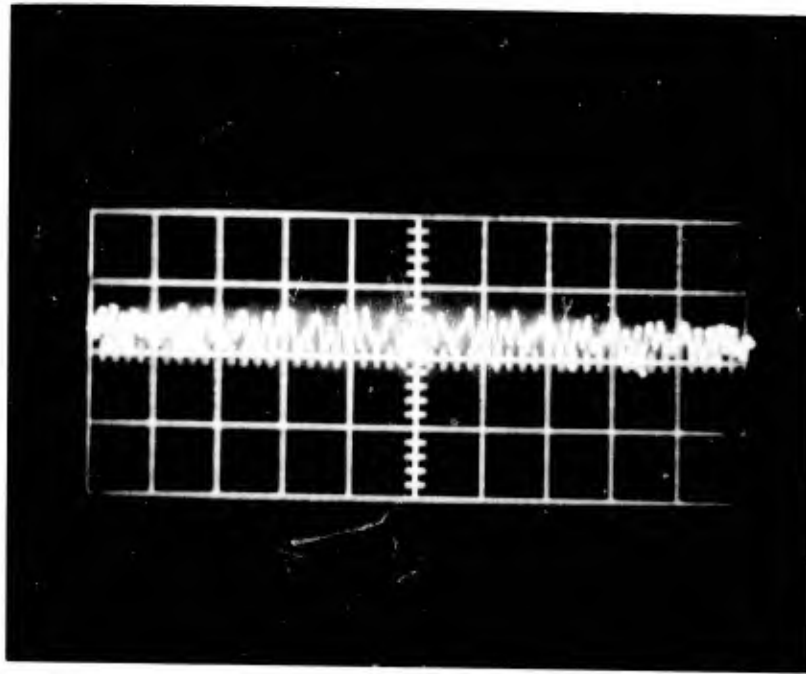
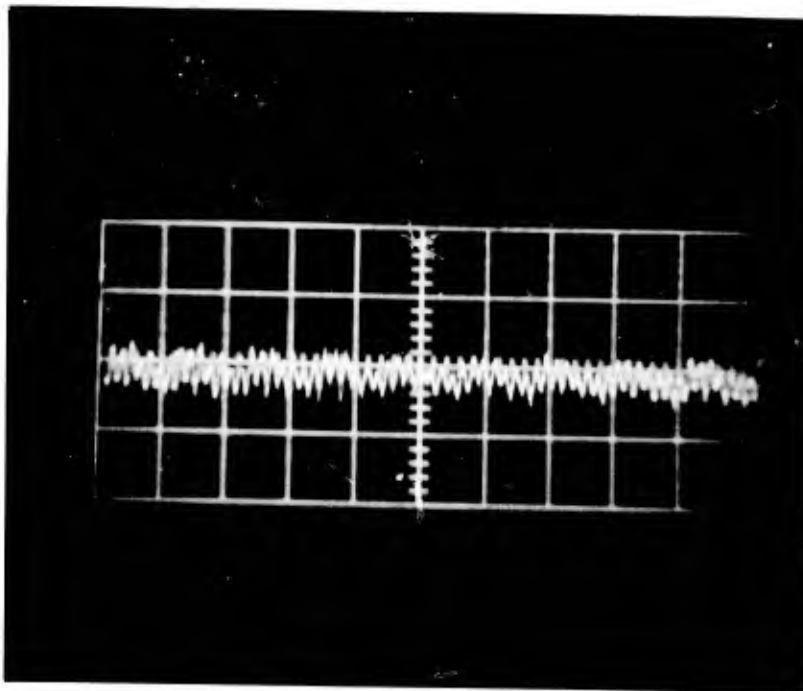


Figure 11. Deadweight Torsion Test Machine



220 PERCENT LOAD, 8.46×10^5 CYCLES



100 PERCENT LOAD, 9.09×10^5 CYCLES

Figure 12. Test Box Vibration Signatures for SK21988 (Serial No. 1, Side B) and SK21989 (Serial No. 1) at Scale of 0.05 Volts per Centimeter.

3. Complete the test load schedule by conducting rotating tests for a maximum of 3×10^6 cycles (or failure) at each of the specified load levels.

Gear Stress Calculations

The gear stress levels presented in this report were calculated by an existing Boeing-Vertol computer program which uses the following AGMA (American Gear Manufacturers Association) standards in the analysis:

- 220.02 Rating the strength of spur gear teeth
- 210.02 Surface durability of spur gears

AGMA 220.02 rates the bonding strength of spur gears as follows:

$$S_t = \frac{W_t \cdot K_o}{K_t} \times \frac{P_d}{F} \times \frac{K_s \cdot K_m}{J} \quad (1)$$

Where

W_t = transmitted tangential load (pounds)
 K_o = overload factor
 K_v = dynamic factor
 P_d = diametral pitch
 F = face width
 K_s = size factor
 K_m = load distribution factor
 J = geometry factor

For the test gears utilized in this program assume:

$$K_o, K_v, K_s, K_m = 1.0 \quad (2)$$

then,

$$S_t = \frac{W_t \times 1}{1} \times \frac{5.333}{.500} \times \frac{1 \times 1}{.3808} \quad (3)$$

$$S_t = 28.009 \times W_t \text{ (see Figure 13)} \quad (4)$$

AGMA 210.01 rates the surface durability of spur gears as follows:

$$S_c = C_p \sqrt{\frac{W_t \cdot C_o}{c_v} \frac{C_s}{d \cdot F} \frac{C_m \cdot C_f}{I}} \quad (5)$$

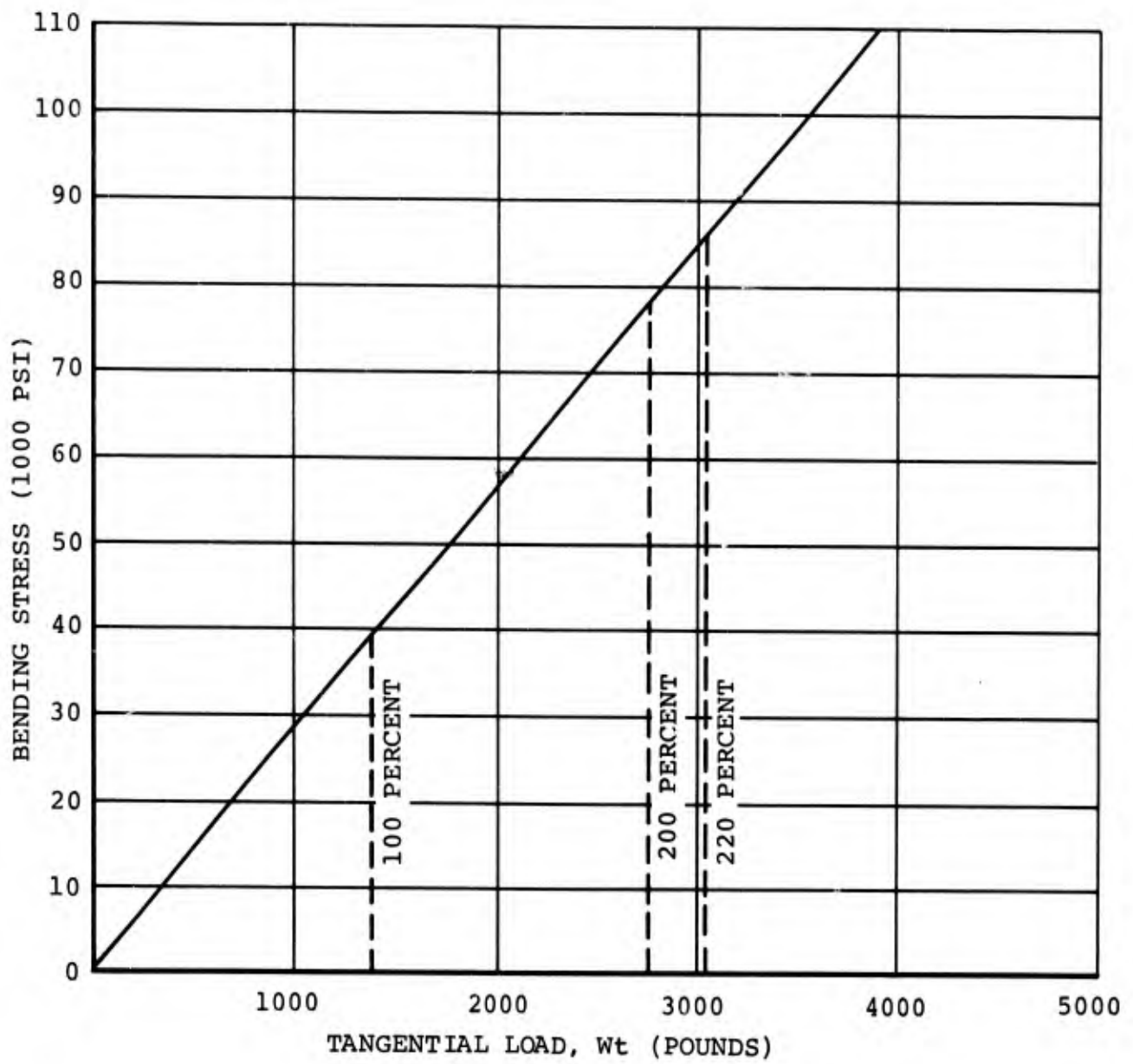


Figure 13. Test Gear Bending Stress (SK21984, SK21985, SK21988, and SK21989)

where S_c = calculated contact stress number
 C_p = elastic coefficient (2300 for steel gears)
 W_t = transmitted tangential load at operating pitch diameter (pounds)
 C_o = overload factor
 C_v = dynamic factor
 d = pinion operating pitch diameter (inches)
 F = face width (inches)
 C_s = size factor
 C_m = load distribution factor
 I = geometry factor
 C_f = surface condition factor

For the test gears used in this program, assume:

$$C_o, C_v, C_s, C_m, C_f = 1.0 \quad (6)$$

then,

$$S_c = 2300 \sqrt{\frac{W_t \times 1}{1} \times \frac{1.}{4.5 \times .50} \times \frac{1 \times 1}{.10}} \quad (7)$$

$$S_c = 2300 \sqrt{\frac{W_t}{.225}} \quad (\text{see Figure 14}) \quad (8)$$

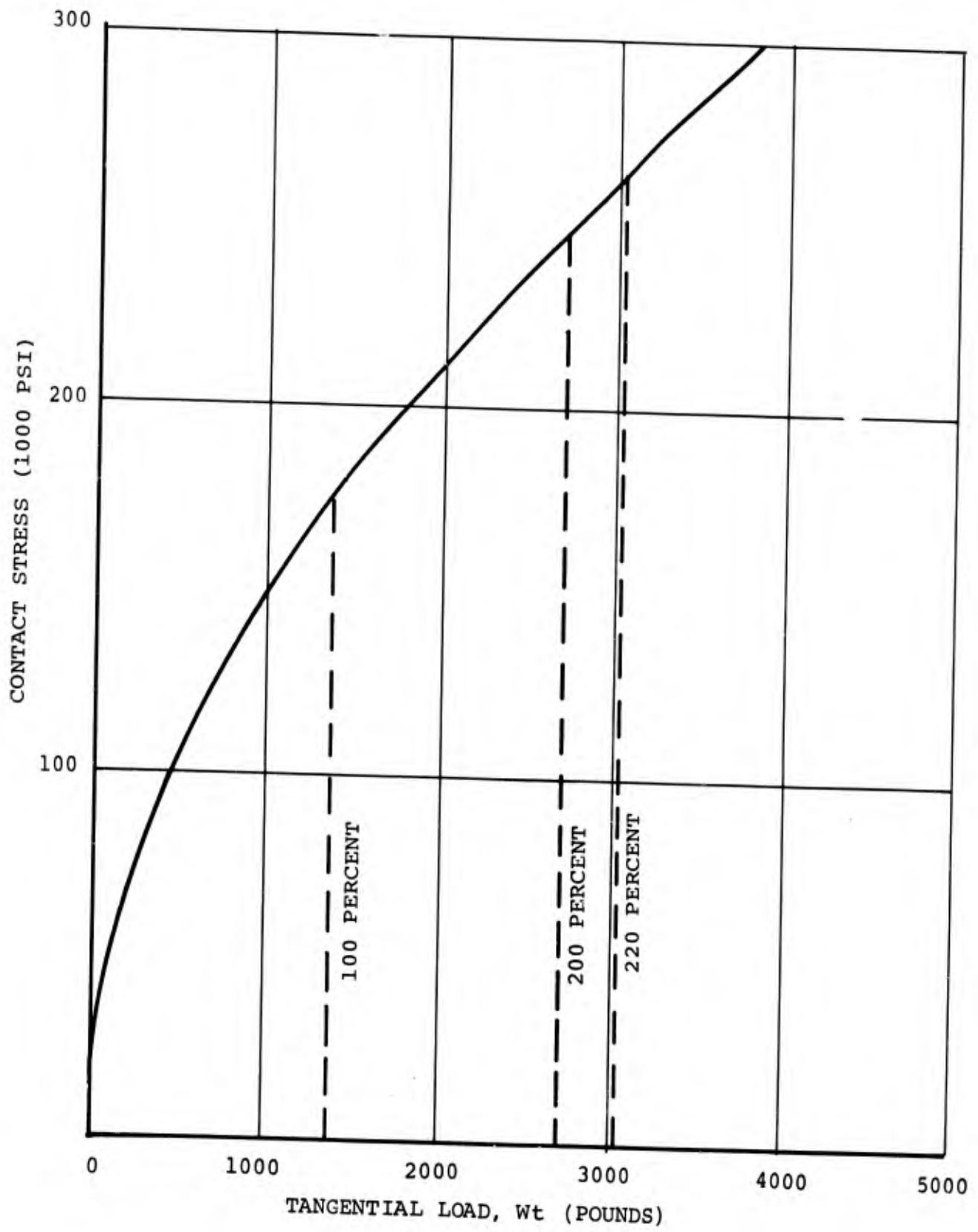


Figure 14. Test Gear Pitch Line Contact Stress (SK21984, SK21985, SI21988, and SK21989)

4. TEST RESULTS

Test Data

The objective of this experimental test program was to investigate candidate gear steels for increased surface load capacity, in comparison to the conventional (baseline) AISI 9310 gear steel.

A summary of the test results of this experimental program is shown in Tables 6 and 7 which contain the pertinent information obtained during the test phase, including part number, serial number, gear type, load levels, test cycles and failure mode.

The basic 100 percent design load level for this program was established as 2750 pounds per inch of face (3094 inch-pounds of torque) resulting in a bending stress of 38,513 psi and a contact stress at the pitch line of 179,800 psi.

The 100 percent design load was determined by using the current allowable pitch line contact stress of 150,000 psi for spur gears in existing Boeing-Vertol helicopter transmissions and applying a factor of 1.4 to account for the difference in operational characteristics of the Boeing-Vertol Gear Research Test Stand.

The basic load schedule for the baseline test gears SK21984 gear and SK21985 pinion (AISI 9310 steel) is presented in Table 4. The basic load schedule for the advanced gear material test gears SK21988 gear and SK21989 pinion (VASCO-X2, .24 carbon steel) is presented in Table 5.

The criteria for definition of a failure for all of the test gears used in this experimental program were established as follows: A minimum of one (1) pit per tooth, on each of three (3) non-adjacent teeth having a minimum dimension of 1/16-inch shall constitute a failure.

Discussion

Initial light scoring was observed at the 100 percent load level on most of the AISI 9310 gear test specimens. However, this condition appeared to stabilize and heal over at the conclusion of the 100 percent load run.

Initial light scoring is a state of lubrication phenomena which develops as a result of surface asperity contacts. The local

TABLE 4. LOAD SCHEDULE FOR BASELINE AISI 9310
STEEL GEARS

Run No.	Tangential Load, Wt (lb)	Pinion Torque (in.-lb)	Percent Load	Number of Test Cycles
1	687	1547	50	5.5×10^4
2	1375	3094	100	3×10^6
3	2200	4950	160	3×10^6
4	2612	5879	190	3×10^6

TABLE 5. LOAD SCHEDULE FOR VASCO-X2 STEEL GEARS

Run No.	Tangential Load, Wt (lb)	Pinion Torque (in.-lb)	Percent Load	Number of Test Cycles
1	687	1547	50	5.5×10^4
2	1375	3094	100	3×10^6
3	2612	5879	190	3×10^6
4	3025	6807	220	3×10^6
5	3437	7735	250	3×10^6

TABLE 6. SUMMARY OF TEST RESULTS FOR AISI 9310 STEEL TEST GEARS (SPUR)

PART NUMBER	SERIAL NUMBER	NAME	SIDE	LOAD LEVEL		BENDING STRESS		CONTACT STRESS		NUMBER OF TEST CYCLES	RESULTS
				PERCENT	PSI	PSI	PSI				
SK21984	3	Gear	A	100	38,513	179,799	3 x 10 ⁶	Runout			Runout
SK21985	3	Pinion	A	160	61,621	227,428	3 x 10 ⁶	Runout			Runout
				190	73,175	247,835	*3 x 10 ⁶	Pitting Failure			Pitting Failure - Pinion
SK21984	3	Gear	B	100	38,513	179,799	3 x 10 ⁶	Runout			Runout
SK21985	3	Pinion	B	160	61,621	227,428	1.3 x 10 ⁶	Pitting Failure			Pitting Failure - Pinion
SK21984	2	Gear	A	100	38,513	179,799	3 x 10 ⁶	Runout			Runout
SK21985	2	Pinion	A	160	61,621	227,428	3 x 10 ⁶	Runout			Runout
				190	73,175	247,835	6.2 x 10 ⁵	Pitting Failure			Pitting Failure - Pinion
SK21984	2	Gear	B	100	38,513	179,799	3 x 10 ⁶	Runout			Runout
SK21985	2	Pinion	B	160	61,621	227,428	2.3 x 10 ⁶	Pitting Failure			Pitting Failure - Pinion
SK21984	1	Gear	A	100	38,513	179,799	3 x 10 ⁶	Runout			Runout
SK21985	1	Pinion	A	160	61,621	227,428	1.5 x 10 ⁶	Pitting Failure			Pitting Failure - Pinion
SK21984	1	Gear	B	100	38,513	179,799	3 x 10 ⁶	Runout			Runout
SK21985	1	Pinion	B	160	61,621	227,428	3 x 10 ⁶	Pitting Failure			Pitting Failure - Pinion
SK21984	5	Gear	A	100	38,513	179,799	3 x 10 ⁶	Runout			Runout
SK21985	5	Pinion	A	160	61,621	227,428	3 x 10 ⁶	Runout			Runout
				190	73,175	247,835	3 x 10 ⁶	Pitting Failure			Pitting Failure - Pinion

31

D

SK21985	2	Gear	A	100	38,513	179,799	3 x 106	Runout
		Pinion	A	160	61,621	227,428	3 x 106	Runout
				190	73,175	247,835	6.2 x 105	Pitting Failure - Pinion
SK21984	2	Gear	B	100	38,513	179,799	3 x 106	Runout
SK21985	2	Pinion	B	160	61,621	227,428	2.3 x 106	Pitting Failure - Pinion
SK21984	1	Gear	A	100	38,513	179,799	3 x 106	Runout
SK21985	1	Pinion	A	160	61,621	227,428	1.5 x 106	Pitting Failure - Pinion
SK21984	1	Gear	B	100	38,513	179,799	3 x 106	Runout
SK21985	1	Pinion	B	160	61,621	227,428	3 x 106	Pitting Failure - Pinion
SK21984	5	Gear	A	100	38,513	179,799	3 x 106	Runout
SK21985	5	Pinion	A	160	61,621	227,428	3 x 106	Runout
				190	73,175	247,835	3 x 106	Pitting Failure - Pinion
SK21984	5	Gear	B	100	38,513	179,799	3 x 106	Runout
SK21985	5	Pinion	B	160	61,621	227,428	1.5 x 106	Pitting Failure - Pinion
SK21984	6	Gear	A	100	38,513	179,799	3 x 106	Runout
SK21985	4	Pinion	A	160	61,621	227,428	1.3 x 106	Pitting Failure - Pinion
SK21984	6	Gear	B	100	38,513	179,799	3 x 106	Runout
SK21985	4	Pinion	B	160	61,621	227,428	1.97 x 106	Pitting Failure - Pinion

*The original pit on the pinion of approximately .20 inches occurred at 1.3 x 10⁶ cycles and this data was utilized in the statistical data.

B

TABLE 7. SUMMARY OF TEST RESULTS FOR VASCO-X2 STEEL TEST GEARS

PART NUMBER	SERIAL NUMBER	NAME	SIDE	LOAD LEVEL PERCENT	BENDING STRESS		CONTACT STRESS PSI	NUMBER OF TEST CYCLES	RESULTS
					PSI	PSI			
SK21988	1	Gear	A	100	38,513	179,799	179,799	3 x 106	Runout
SK21989	1	Pinion	A	190	73,175	247,835	247,835	3 x 106	Runout
				220	84,729	266,678	266,678	1.42 x 106	Pitting Failure - Pinion
SK21988	1	Gear	B	100	38,513	179,799	179,799	3 x 106	Runout
SK21989	1	Pinion	B	190	73,175	247,835	247,835	3 x 106	Runout
				220	84,729	266,678	266,678	1.3 x 106	Pitting Failure - Pinion
SK21988	2	Gear	A	100	38,513	179,799	179,799	3 x 106	Runout
SK21989	2	Pinion	A	190	73,175	247,835	247,835	3 x 106	Runout
				220	84,729	266,678	266,678	3 x 106	Runout
				250	96,283	284,280	284,280	5 x 105	Pitting Failure - Pinion
SK21988	2	Gear	B	100	38,513	179,799	179,799	3 x 106	Runout
SK21989	2	Pinion	B	190	73,175	247,835	247,835	3 x 106	Runout
				220	84,729	266,678	266,678	3 x 106	Runout
				250	96,283	284,280	284,280	7.6 x 105	Pitting Failure - Pinion
SK21988	3	Gear	A	100	38,513	179,799	179,799	3 x 106	Runout
SK21989	3	Pinion	A	190	73,175	247,835	247,835	3 x 106	Runout
				220	84,729	266,678	266,678	3 x 106	Runout
				250	96,283	284,280	284,280	7.6 x 105	Pitting Failure - Pinion
SK21988	3	Gear	B	100	38,513	179,799	179,799	3 x 106	Runout
SK21989	3	Pinion	B	190	73,175	247,835	247,835	3 x 106	Runout
				220	84,729	266,678	266,678	1.3 x 106	Pitting Failure - Pinion
SK21988	3	Gear	B	100	38,513	179,799	179,799	3 x 106	Runout
SK21989	3	Pinion	B	190	73,175	247,835	247,835	3 x 106	Runout
				220	84,729	266,678	266,678	3 x 106	Pitting Failure - Pinion

D

Pinion

SK21988	2	Gear	B	100	38,513	179,799	3 x 106	Runout
SK21989	2	Pinion	B	190	73,175	247,835	3 x 106	Runout
				220	84,729	266,678	3 x 106	Runout
				250	96,283	284,280	7.6 x 105	Pitting Failure - Pinion
SK21988	3	Gear	A	100	38,513	179,799	3 x 106	Runout
SK21989	3	Pinion	A	190	73,175	247,835	3 x 106	Runout
				220	84,729	266,678	1.3 x 106	Pitting Failure - Pinion
SK21988	3	Gear	B	100	38,513	179,799	3 x 106	Runout
SK21989	3	Pinion	B	190	73,175	247,835	3 x 106	Runout
				220	84,729	266,678	3 x 106	Pitting Failure - Pinion
SK2198	4	Gear	A	100	38,513	179,799	3 x 106	Runout
SK21989	4	Pinion	A	190	73,175	247,835	3 x 106	Runout
				220	84,729	266,678	3 x 106	Runout
				250	96,283	284,280	9.8 x 105	Pitting Failure - Pinion
SK21988	4	Gear	B	100	38,513	179,799	3 x 106	Runout
SK21989	4	Pinion	B	190	73,175	247,835	3 x 106	Runout
				220	84,729	266,678	3 x 106	Pitting Failure - Pinion
SK21988	5	Gear	A	100	38,513	179,799	3 x 106	Runout
SK21989	5	Pinion	A	190	73,175	247,835	3 x 106	Runout
				220	84,729	266,678	3 x 106	Runout
				250	96,283	284,280	3.9 x 105	Pitting Failure - Pinion
SK21988	5	Gear	B	100	38,513	179,799	3 x 106	Runout
SK21989	5	Pinion	B	190	73,175	247,835	3 x 106	Runout
				220	84,729	266,678	3 x 106	Runout
				250	96,283	284,280	1.43 x 106	Pitting Failure - Pinion

B

high spots concentrate the load in these areas permitting metal-to-metal contact, along with concentrated pressures. Continued operation at moderate loads will eventually wear down the localized high spots (asperities) and thereby permit improved load distribution which in turn will result in a healed over (polished) condition.

The frosting condition on the pinion dedendum was usually observed at the 160 percent load level; however, the severity of this condition was not apparent to normal observation. The final condition of the AISI 9310 gear test specimens, which displayed the typical pitting and/or spalling condition is presented in Figures 15 through 19. These figures also show the typical frosting condition identified by the etch-like appearance of the surface on the pinion dedendum. Under magnification, the frosted surface appears to contain a field of micro-pits with no evidence of radial welding and/or tear marks.

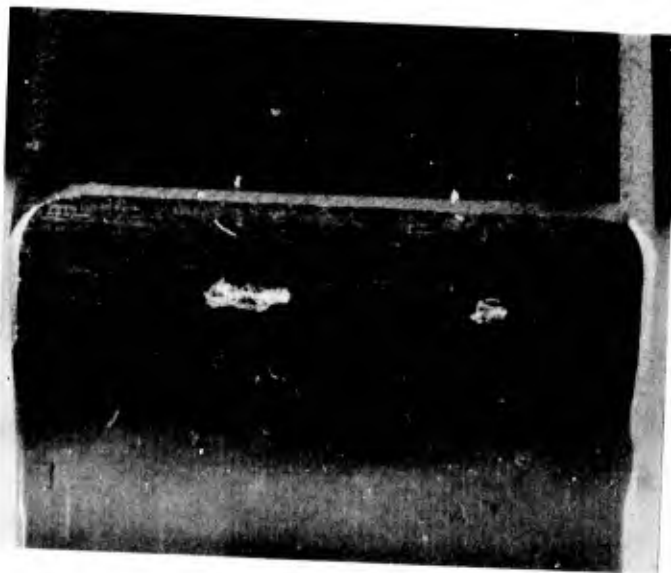
The test program for the VASCO-X2 gear test specimens was completed with little or no evidence of scoring except for the last test set, SK21989, Serial No. 5. At the 190 percent load level for this set, a significant change in the vibration signature was observed and the test was interrupted. Subsequent removal and inspection of the gears, bearings, and shafting revealed that the inner race bearing spacer had excessive longitudinal play. The test pinion sustained medium scoring from the first point of contact to a point above pitch line. The gear member sustained medium scoring from the outside diameter to a point below the pitch line. The bearing spacer condition was corrected and the test program continued.

In most cases, a frosting condition was observed during the 190 percent load run. This condition appeared to taper across the face width with the widest portion located at the end closest to the mounting shoulder. The final condition of the VASCO-X2 gear test specimens displaying the typical pitting and/or spalling condition is presented in Figures 20 through 23. These same figures show the typical frosting condition, identified by the etch-like appearance of the surface, on the pinion dedendum. They also show the highly polished condition of the remaining tooth surface, with no evidence of scoring. Under magnification, the frosted surface appears to contain a field of micro-pits with no evidence of radial welding and/or tear marks.

The pitting condition sustained by the gear test specimens for both materials under investigation appear to be typical of destructive pitting usually found in the dedendum of the driving member in a reduction gear drive. This condition is characterized by the appearance of large pits, in excess of 1/32-inch in diameter in the dedendum region. This type of pitting failure will usually progress in size and number of pits, with repeated stress cycles, and can eventually lead to catastrophic failure. Assuming that the material integrity is sound, and that

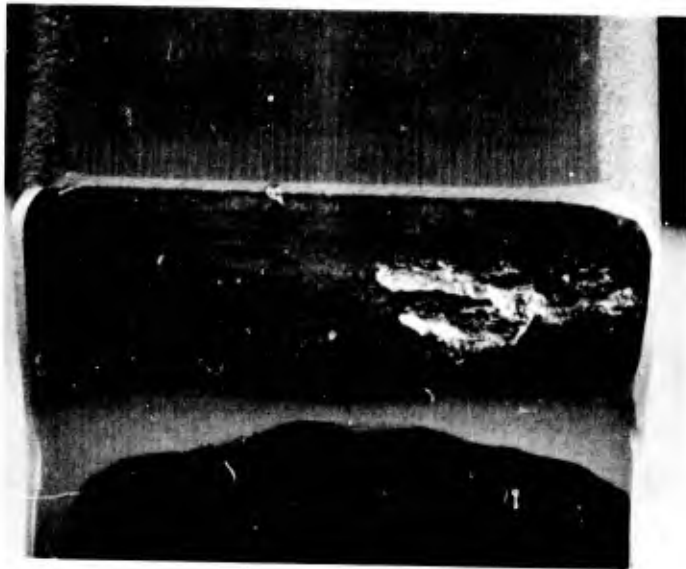


SIDE A, TOOTH 2, 190 PERCENT LOAD, 6.2×10^5 CYCLES

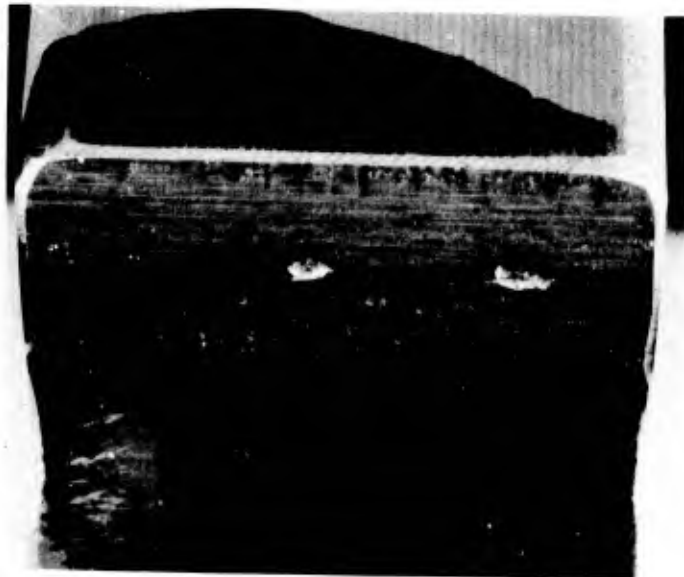


SIDE B, TOOTH 21, 160 PERCENT LOAD, 2.3×10^6 CYCLES

Figure 15. Final Condition of AISI 9310 Steel Test Pinion (SK21985, Serial No. 2).

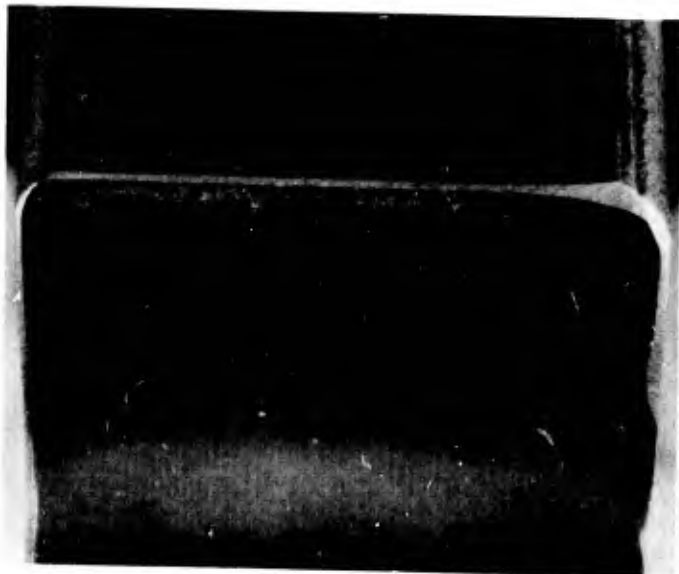


SIDE A, TOOTH 16, 190 PERCENT LOAD, 3.0×10^6 CYCLES



SIDE B, TOOTH 22, 160 PERCENT LOAD, 1.3×10^6 CYCLES

Figure 16. Final Condition of AISI 9310 Steel Test Pinion (SK21985, Serial No. 3).

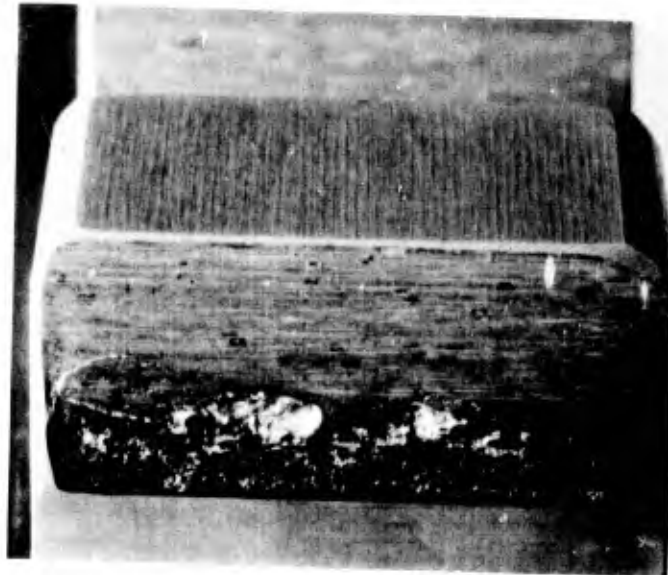


SIDE A, TOOTH 4, 190 PERCENT LOAD, 3.0×10^6 CYCLES

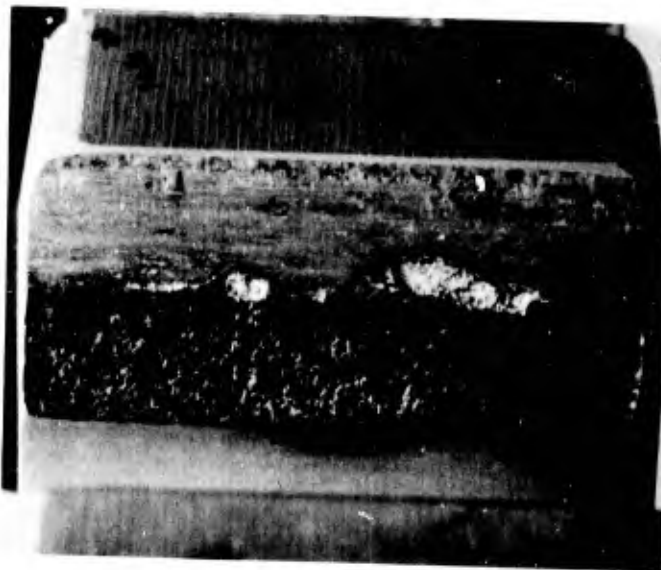


SIDE B, TOOTH 4, 160 PERCENT LOAD, 1.5×10^6 CYCLES

Figure 17. Final Condition of AISI 9310 Steel Test Pinion (SK21985, Serial No. 5).

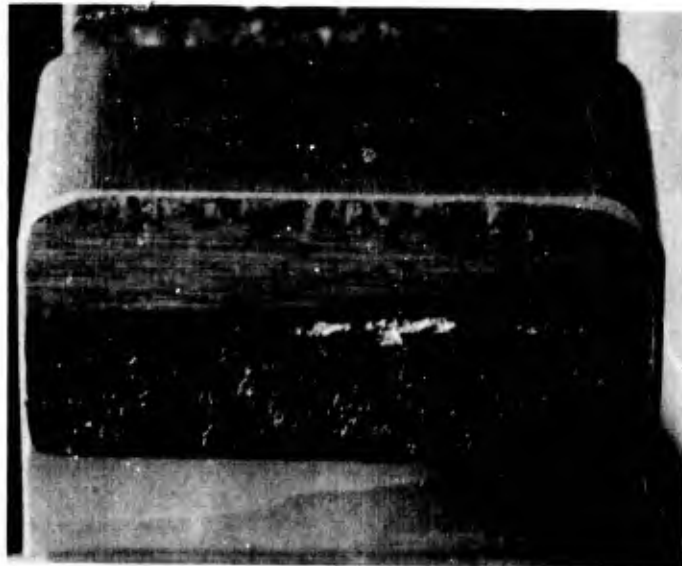


SIDE A, TOOTH 8, 160 PERCENT LOAD, 1.3×10^6 CYCLES

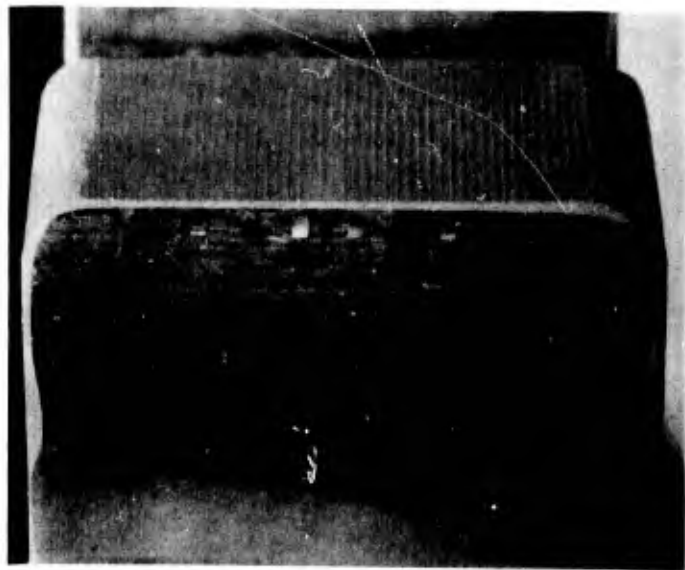


SIDE B, TOOTH 23, 160 PERCENT LOAD, 1.97×10^6 CYCLES

Figure 18. Final Condition of AISI 9310 Steel Test Pinion (SK21985, Serial No. 4).

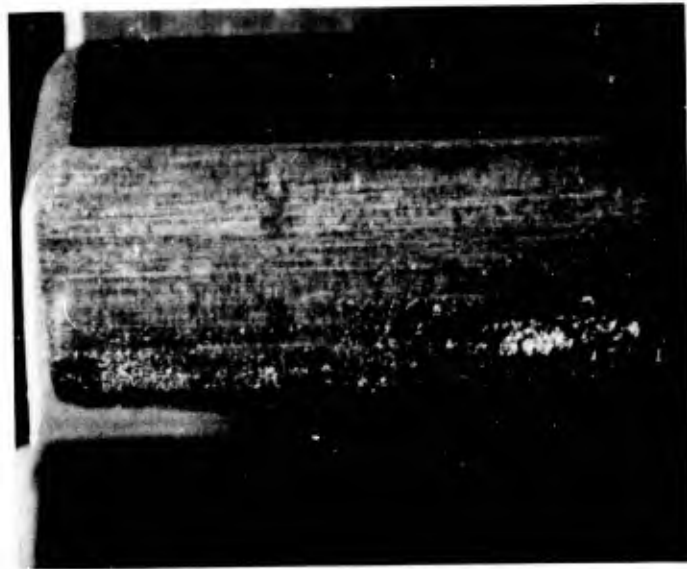


SIDE A, TOOTH 1, 160 PERCENT LOAD, 1.5×10^6 CYCLES

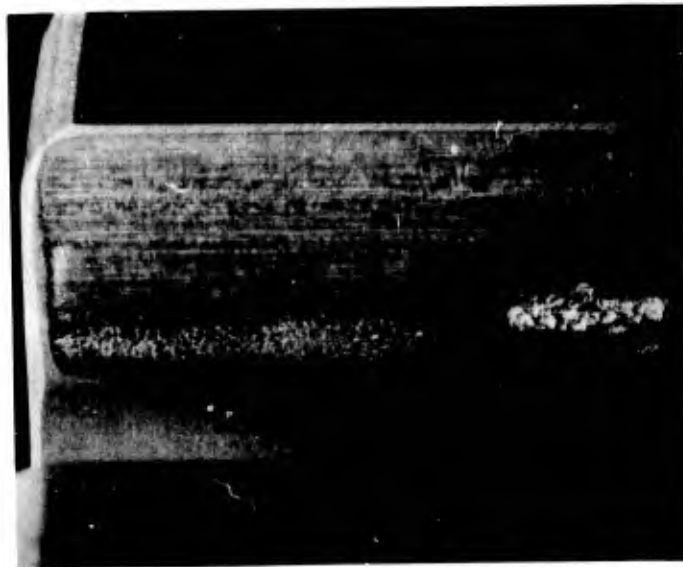


SIDE B, TOOTH 2, 160 PERCENT LOAD, 3.0×10^6 CYCLES

Figure 19. Final Condition of AISI 9310 Steel Test Pinion (SK21985, Serial No. 1).

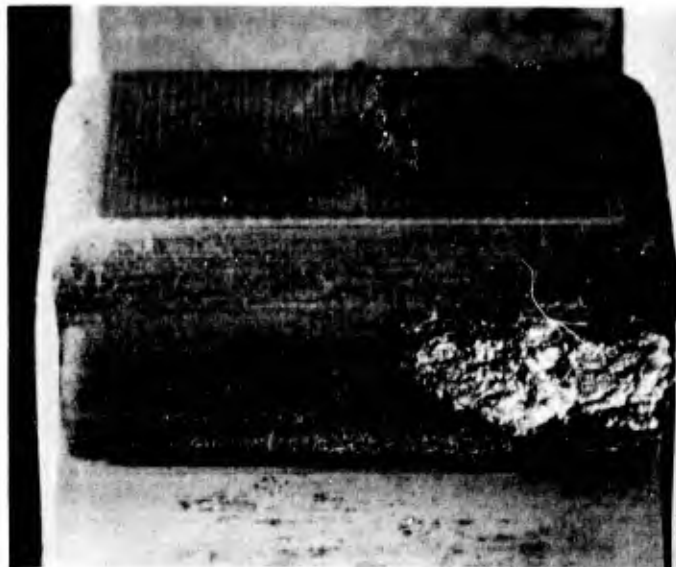


SIDE A, TOOTH 16, 250 PERCENT LOAD, 9.8×10^5 CYCLES

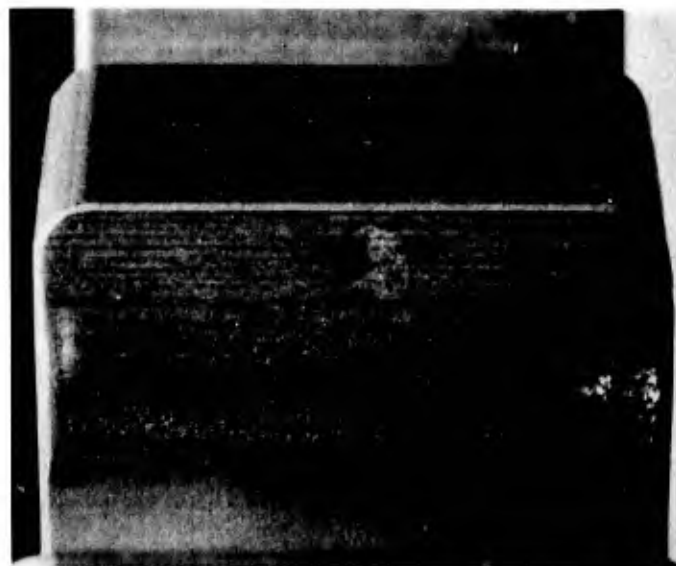


SIDE B, TOOTH 17, 220 PERCENT LOAD, 3×10^6 CYCLES

Figure 20. Final Condition of VASCO-X2 Steel Test Pinion (SK21985, Serial No. 4).

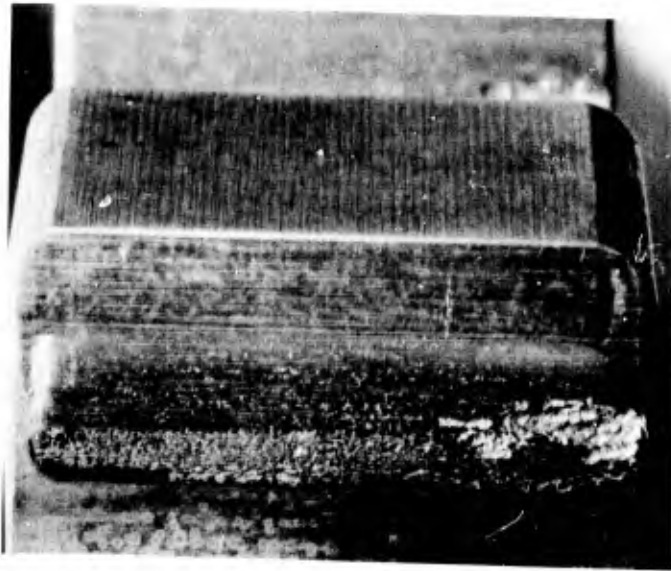


SIDE A, TOOTH 11, 220 PERCENT LOAD, 1.3×10^6 CYCLES

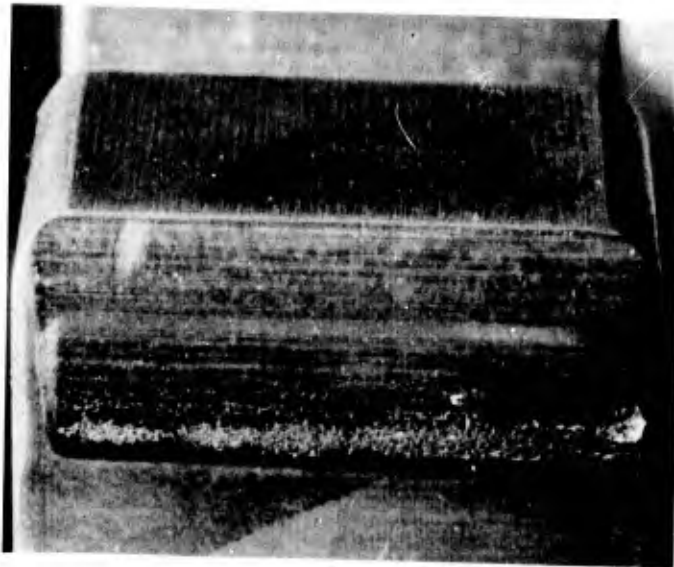


SIDE B, TOOTH 14, 220 PERCENT LOAD, 3×10^6 CYCLES

Figure 21. Final Condition of VASCO-X2 Steel Test Pinion (SK21989, Serial No. 3).

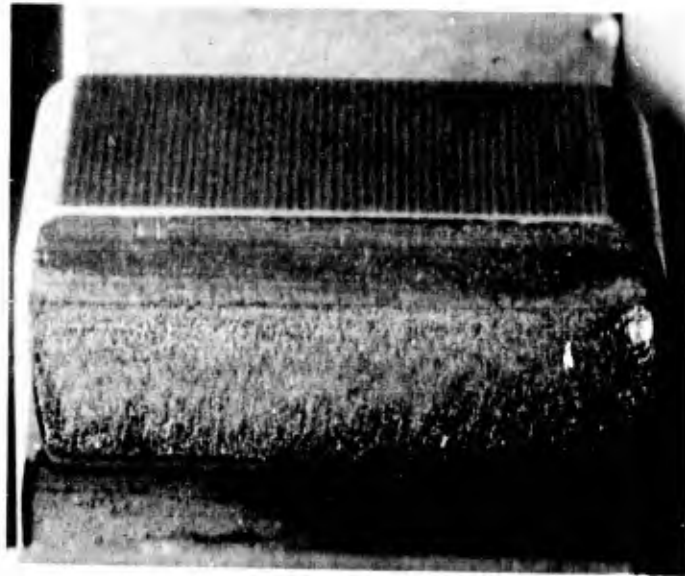


SIDE A, TOOTH 8, 250 PERCENT LOAD, 5×10^5 CYCLES

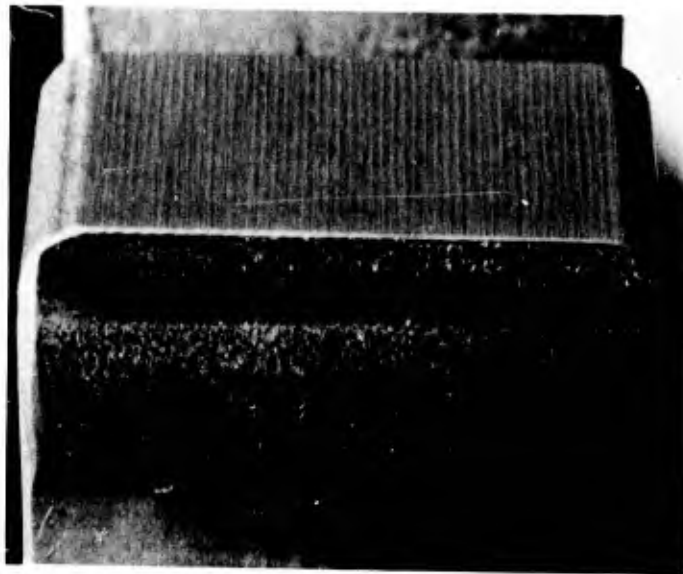


SIDE B, TOOTH 13, 250 PERCENT LOAD, 7.6×10^6 CYCLES

Figure 22. Final Condition of VASCO-X2 Steel Test Pinion (SK21989, Serial No. 2).



SIDE A, TOOTH 16, 250 PERCENT LOAD, 3.9×10^5 CYCLES



SIDE B, TOOTH 13, 250 PERCENT LOAD, 1.4×10^6 CYCLES

Figure 23. Final Condition of VASCO-X2 Steel Test Pinion (SK21989, Serial No. 5).

fabrication process specifications are successfully completed, this type of failure usually indicates that the operating load sustained at the time of failure is in excess of the material surface endurance limit.

All of the gear test specimens (AISI 9310 and VASCO-X?) were inspected by the nital etch process after completion of the test program. This inspection revealed a contact burn condition in the pinion dedendum on all of the AISI 9310 steel test pinions. This condition is usually indicative of high temperature and/or concentrated pressure. A micro examination is presented in Figure 24. The photograph displays the burned area, located approximately 0.012 inch above the fillet radius juncture, 0.064-inch in length, and 0.0025-inch deep. This condition was not evident on the VASCO-X2 steel test pinions.

Data Analysis

Test data evaluation was accomplished using statistical methods to establish reliable surface contact stress endurance value limits for the two materials under investigation. The life factor C in AGMA Standard 210.02, "Surface Durability (Pitting) of Spur Gear Teeth", was used to project the contact stress endurance limit to 10 million cycles for the test data points. Figure 25 represents the surface durability life factor which was employed for projection of the test data.

All of the test data points, for both materials, listed in Tables 6 and 7 were projected for the expected endurance limit at 10 million cycles. As shown in Figure 25, the life factor C_L becomes unity at 10 million cycles, indicating that the surface fatigue endurance limit is achieved at that point. The number of test cycles to failure for each data point was used to determine the correct life factor for application to each data point. This life factor was then employed to determine the calculated endurance limit at 10 million cycles by dividing the contact stress at failure, for each data point, by the respective life factor. A listing of the specific data points, life correction factors, and calculated endurance limits is presented in Table 9.

An existing Boeing-Vertol computer program was used for the statistical data evaluation. This study was accomplished by employing the following method of analysis. The various calculated surface endurance stress indices were used to determine the mean (50 percent failure rate) endurance stress, the unbiased standard deviation, and the 99 percent confidence limits for the mean endurance limit. Figure 26 presents a plot of the test data points with the mean endurance limit and the associated 99 percent confidence limits. The plotted data presented in Figure 26 is also listed in tabular form in Table 8.

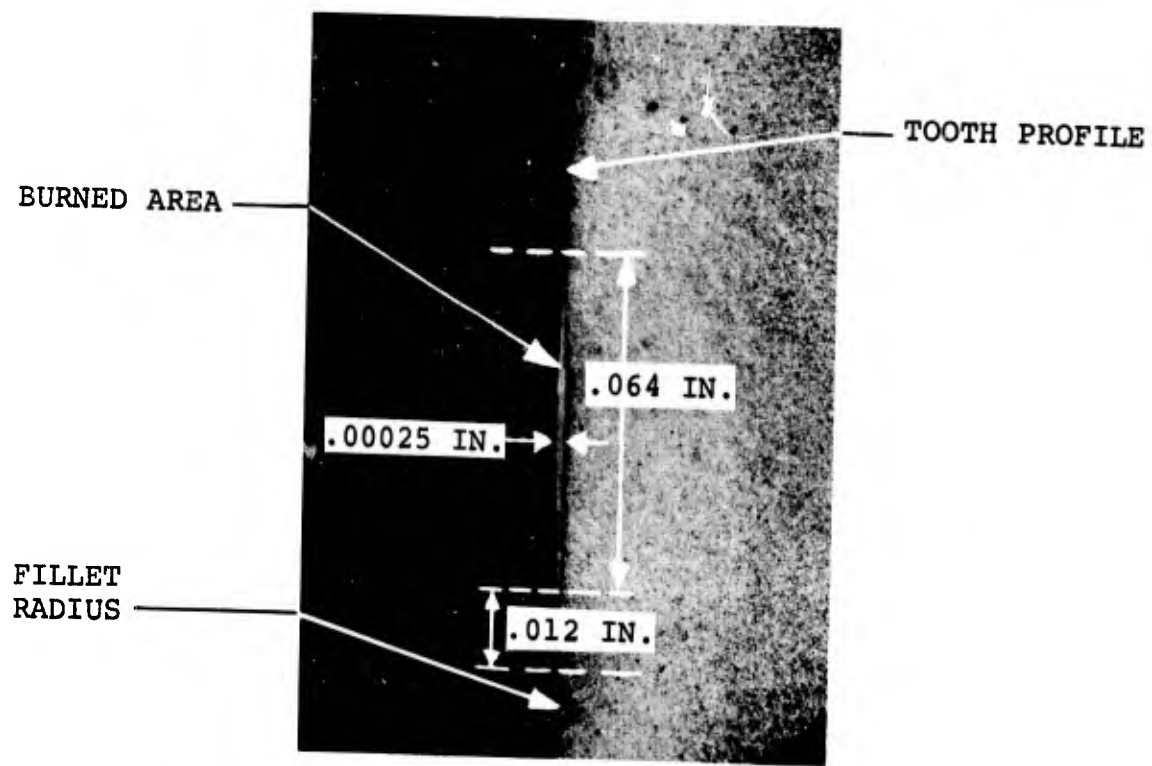


Figure 24. Contact Burn on AISI 9310 Steel Pinion (Scale 25x)

TABLE 8. RESULTS OF STATISTICAL ANALYSIS

Material	Number of Data Points Analyzed	Mean (50% Failure) Endurance Limit at 10 ⁷ Cycles (stress, psi)	Lower Limit on Mean (99% Confidence) (stress, psi)	Unbiased Standard Deviation (stress, psi)	Unbiased Standard Deviation at 99.5% Probability (stress, psi)	Stress at 99.5% Probability of Survival (psi)
VASCO-X2 (.24 Carbon-CVM)	10	241,800	235,200	6,400	23,700	211,500
AISI 9310 (AMS 6260)	10	209,000	199,500	9,200	34,100	165,400

TABLE 9. TEST DATA AND CALCULATED ENDURANCE LIMITS

Stress at Failure (psi)	Cycles at Failure	AGMA Standard 210.02 Life Factor, CL	Calculated Endurance Limit at 10^7 Cycles (stress, psi)
<u>VASCO-X2</u>			
284,290	1,430,000	1.127	252,250
284,290	980,000	1.1505	247,100
284,290	760,000	1.168	243,400
284,290	500,000	1.1945	238,000
284,290	390,000	1.2105	234,850
266,690	3,000,000	1.078	247,390
266,690	3,000,000	1.078	247,390
266,690	1,420,000	1.128	236,430
266,690	1,300,000	1.132	235,590
266,690	1,300,000	1.132	235,590
<u>AISI 9310</u>			
247,840	3,000,000	1.078	229,910
247,840	1,300,000	1.132	218,940
247,840	620,000	1.181	209,860
227,430	3,000,000	1.078	210,970
227,430	2,300,000	1.095	207,700
227,430	1,970,000	1.105	205,820
227,430	1,500,000	1.123	202,520
227,430	1,500,000	1.123	202,520
227,430	1,300,000	1.132	200,910
227,430	1,300,000	1.132	200,910

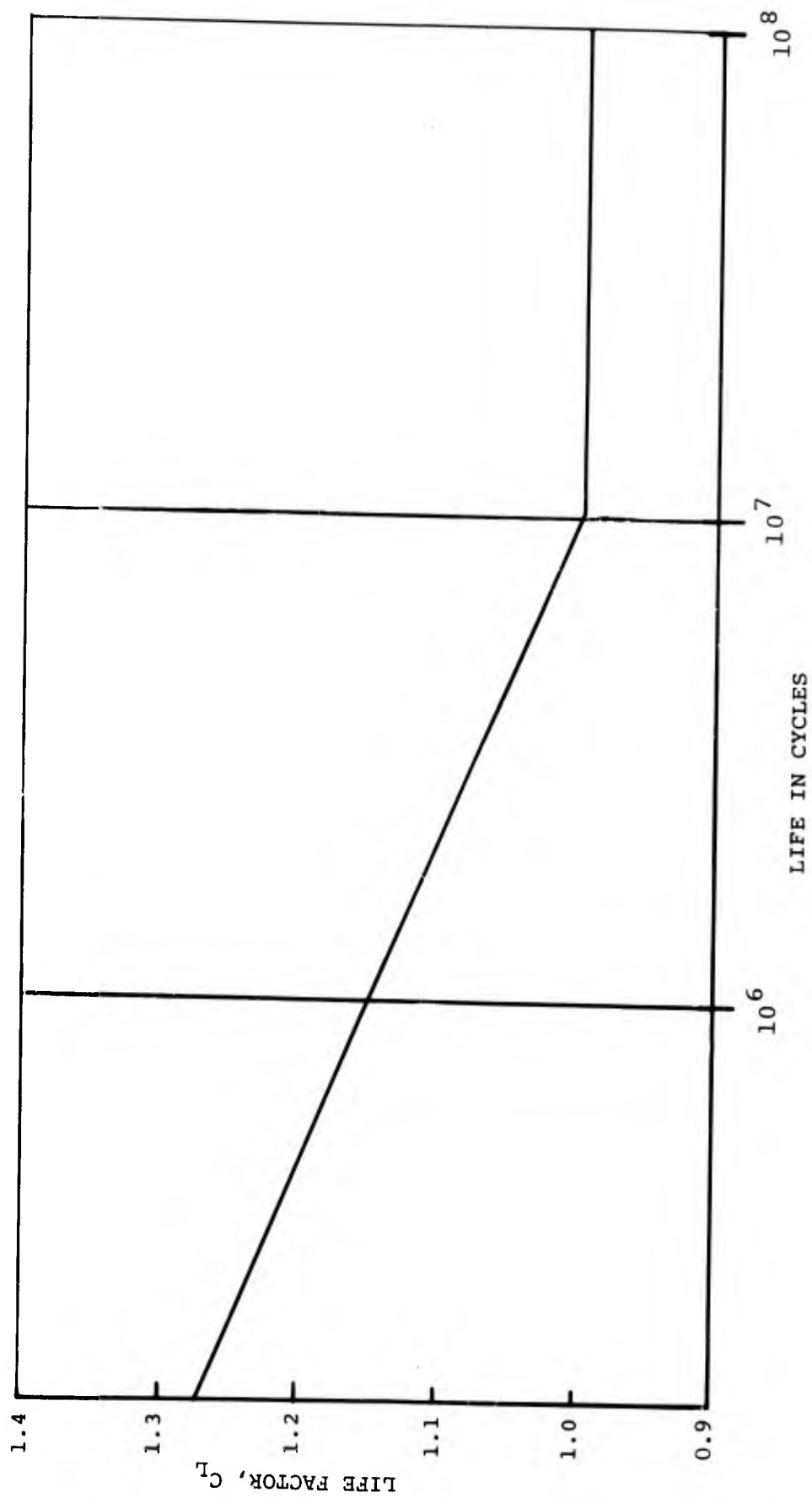


Figure 25. Surface Durability Life Factor (AGMA Standard 219.02)

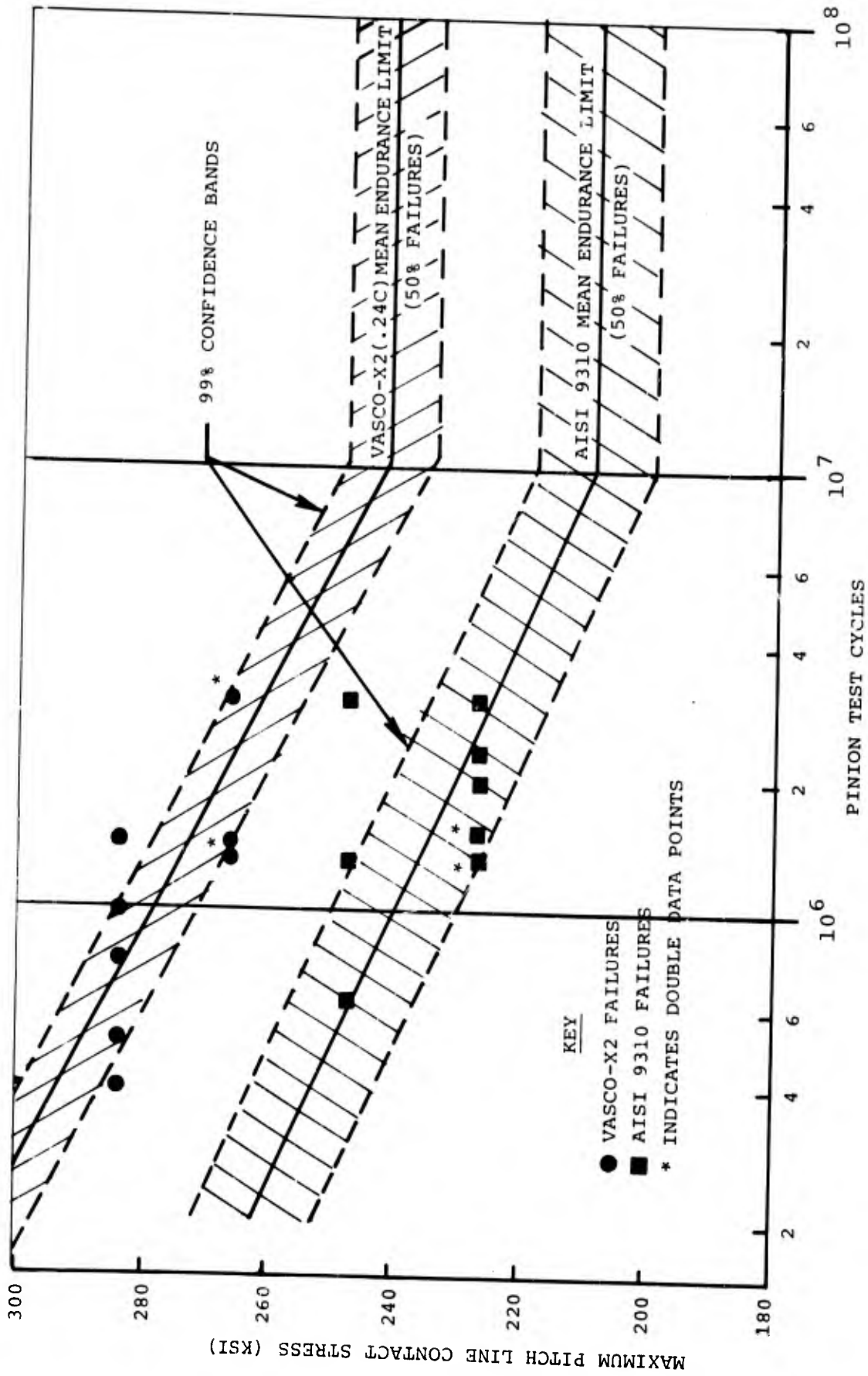


Figure 26 Mean Endurance Limits for a 99.5 Percent Probability of Survival.

The data was further evaluated by assuming the lower limit of the mean as the actual mean, which results in an endurance limit with a 99 percent confidence and a 50 percent probability of survival. The mean endurance limit for a 99.5 percent probability of survival was then calculated using student's t distribution factors, which resulted in the data presented in Figure 27. With these results, a comparison of the two materials can be accomplished at a 99.99 percent probability of survival (standard aircraft gear design practice) with a confidence level of 99 percent.

Analysis of the comparison of the two materials indicates that the mean (50 percent failure rate) endurance limit of the VASCO-X2 steel is approximately 15.7 percent higher than the mean endurance limit of the AISI 9310 steel. However, application of the 99.99 percent probability of survival level with a 99 percent confidence which is normally associated with aircraft design design practice increases this improvement for the VASCO-X2 steel to approximately 33.8 percent.

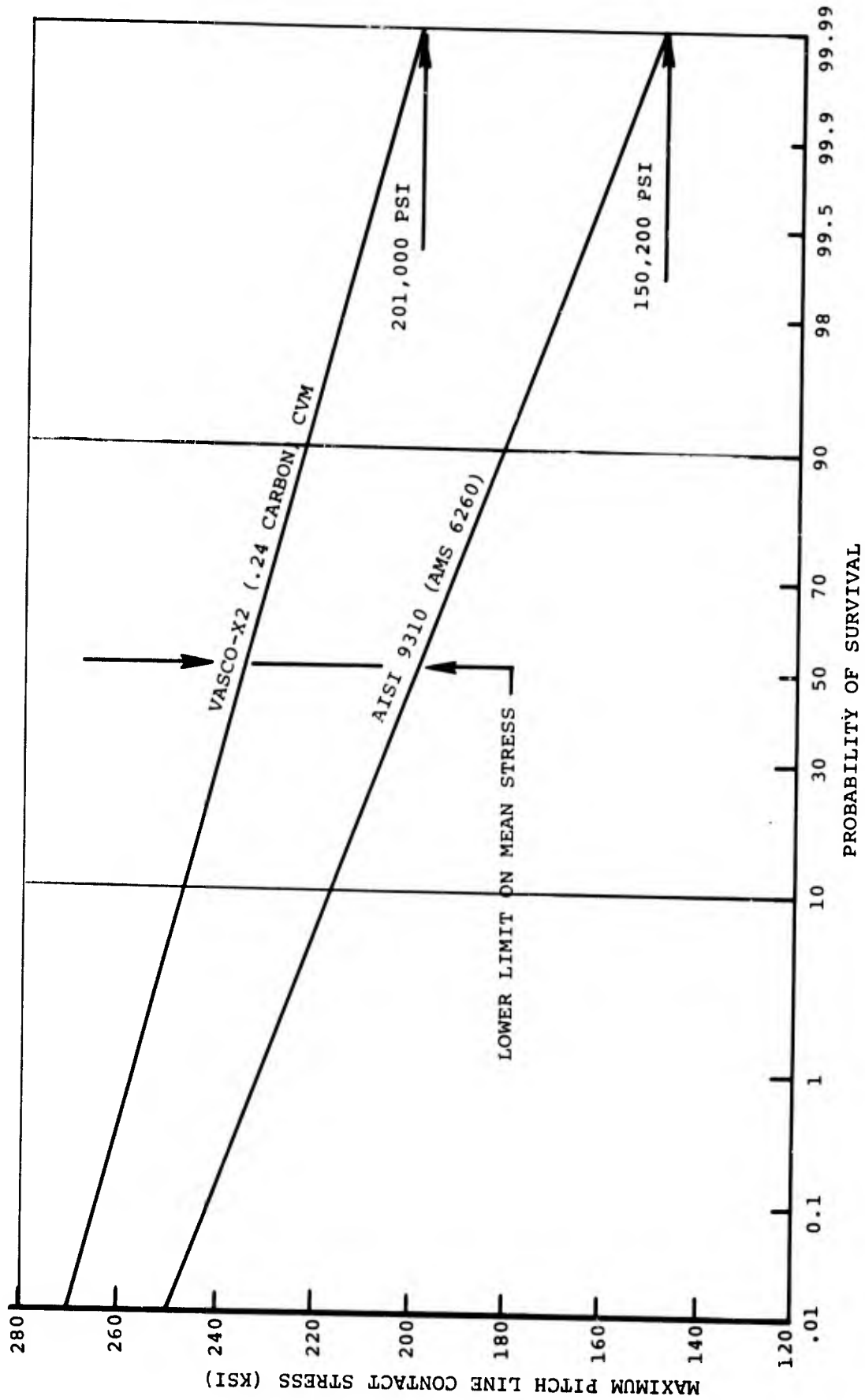


Figure 27 Test Data Points with Mean Endurance Limits at 99 Percent Confidence Level

5. CONCLUSIONS

1. On the basis of the test results obtained from this experimental test program, the VASCO-X2 (.24 carbon) steel test gears achieved load levels of 30 to 60 percent higher than the baseline AISI 9310 (AMS6260) steel test gears.
2. The statistical evaluation of the test results, using typical aircraft confidence and survival levels, indicates an improvement in the design endurance limit for the VASCO-X2 gear specimens of approximately 34 percent.
3. Present design philosophy assumes that there is not substantial difference in allowable contact stress for gear steels of the same quality. The results of this test program indicate that this contention is not necessarily applicable to advanced gear steels.
4. Metallurgical examination of the AISI 9310 gear specimens revealed a contact burn in the pinion dedendum, indicating that excessive temperatures were present. The VASCO-X2 test gear specimen did not exhibit this condition. Since the test gear design and operating condition were the same for the VASCO-2 gears, it is reasonable to assume that the high hot hardness VASCO-X2 steel gears can withstand higher operating temperatures and/or concentrated pressures than the AISI 9310 steel gears.
5. The percentage of retained austenite and degree of carbide network in the VASCO-X2 steel test gears, disclosed by the metallurgical examination, are above the levels normally associated with low alloy steels such as, AISI 9310. Evaluation of the effect of these conditions, on the load carrying capacity of the VASCO-X2 steel test gears, is uncertain at this time since no quantitative controls have ever been established for the microstructure of this material. However, from the chemistry of this material, it seems reasonable to expect a heavier carbide network since carbide formers such as; molybdenum, tungsten, and chromium are present to a greater degree in this material compared to the low alloy steels. The slight variations in chemistry from the basic percentages were negligible and had little or no effect on the load carrying characteristics of the VASCO-X2 steel gears.

6. RECOMMENDATIONS

Based on the results obtained from the experimental testing and evaluation performed during the execution of this program, it is recommended that further work be directed to the following areas.

1. Conduct an experimental test program to determine the capability of operation at higher oil-in temperatures (250°F to 300°F) for the VASCO-X2 material as compared to the current gear steels.
2. Establish a reliable production type heat treat and carburizing specification for VASCO-X2 tool steel to ensure compliance with design specifications and repeatability of manufacture.
3. Fabricate VASCO-X2 steel test specimens using the production type heat-treat and carburizing specification; and conduct single-tooth bending tests for comparison with the previous results from contract number N00156-69-C-0634 (Reference 2).

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13. ABSTRACT Helicopter transmission gear materials are selected mainly for their strength. Sliding behavior is normally improved by hardening the surfaces of the gears. However, pitting and spalling may occur to limit the performance of the transmission, under conditions which are not severe enough to cause tooth breakage. In the search for more reliable gear materials, the VASCO-X2 high hot hardness tool steel had previously demonstrated the capability of carrying 2.40 times the design load for 10 million cycles without evidence of pitting or spalling. Further, there was evidence that the VASCO-X2 test gears developed a protective surface layer on the working tooth under operating loads. The current test program consisted of rotating load tests on gear specimens with a tooth geometry designed to achieve pitting and spalling. VASCO-X2 (.24 carbon) high hot hardness tool steel gears, when tested against baseline gears of AISI 9310 (AMS 6260) aircraft gear steel, demonstrated a 30-percent greater load carrying capability. A protective surface layer appeared to form on the VASCO-X2 gears lowering critical temperatures during operation.		

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT

Advanced Gear Materials
 AISI 9310 Steel
 Gear Boxes and Transmissions

Pitting Failure
 Spalling Failure
 Surface Fatigue
 VASCO-X2 Steel

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There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. **KEY WORDS:** Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.