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ROLLING ELEMENT FATIQUE TESTING OF GEAR MATERIALS

FINAL REPORT

BY
A.H. NAHM

GENERAL ELECTRIC COMPANY
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Project Manager - R. J. Parker
Bearing, Gearing & Transmission Section

16. Abstract

Rolling element fatigue lives of nine alloys were evaluated in the General Electric Rolling Contact (RC) rigs. Test conditions used in the GE RC rigs with cylindrical specimens included a Hertzian stress at 4,826 MPa (700 ksi), a rolling speed of 6.23 m/sec (245 in/sec.). Tests were run with a Type I oil (MIL-L-7808G) at room temperature. Metallurgical analyses were made before and after the RC rig tests. Test data were statistically analyzed using the Weibull distribution function. B-10 lives (10% failure rate) of alloys were compared versus reference alloys, VIM-VAR AISI M-50 and VAR AISI 9310.

Six case carburizing alloys (AISI 9310, CBS600, CBS1000M, EX00014, Vasco X-2 and EX00053) and three through-hardening alloys (AISI M-50, VascoMax 350 and Vasco Matrix II) evaluated in this study showed RCF performance inferior or equivalent to that of AISI 9310 and AISI M-50. It was also found that the effects of vacuum melting processes, different tempering temperatures, freezing cycle during heat treating, shot peening, gold plating and chrome plating employed in the present investigation did not significantly affect RCF life.

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FOREWORD

This program was conducted by the Material and Process Technology Laboratories, Aircraft Engine Group, General Electric Company, under NASA Contract NAS3-14302. The NASA Technical Project Manager was Mr. R. J. Parker of the Bearing, Gearing and Transmission Section, NASA-Lewis Research Center, Cleveland, Ohio 44135. The Technical Project Manager for General Electric was Mr. D. B. Hester.

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Finally, the contributions of Messrs. D. J. Kroeger and S. A. Leighton, who performed the testing and evaluation essential in this type of study, are also gratefully acknowledged.

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I. INTRODUCTION

General Electric Company, under contract to NASA-Lewis Research Center, has conducted this program to investigate the rolling element fatigue characteristics of advanced bearing and gear materials.

Aviation transmission systems are expected to be operated at higher temperature with increased load capacity. This is a general requirement toward better efficiency, not only in commercial jet engines, but also special engines in V/STOL or SST aircraft.

AISI 9310 has been most widely used as a standard aviation alloy because of its ease of processing and excellent case and core properties. However, it is limited to applications where maximum operating temperatures do not exceed 150°C (300°F). There is a definite need for higher temperature gear materials. The materials must be equal to or better than AISI 9310 in terms of performance, processing, and reliability at elevated temperature((200°C+, (400°F+)).

There is also a need for good bearing materials, as well as good gear materials due to increased use of integral bearing/gear designs. For example: helicopter main rotor transmission systems.

Even though a wealth of literature is available regarding rolling contact fatigue lives of various materials (for example: read bibliographies cited in References 1 and 2), there have been few systematic evaluations of various alloys. This is especially true with newly developed bearing and gear materials. Therefore, a major part of this investigation has been directed to study the rolling contact fatigue behavior of various materials under uniform, carefully controlled experimental conditions. Recently, new high temperature gear alloys have been developed. Some of these are EX00014, EX00053, CBS600, CBS1000M and Vasco X-2.

This contract, which has been underway since 1970, has encompassed several related studies:

a) In Tasks I through VII, rolling contact fatigue (RCF) characteristics and failure modes of hollow rolling elements were evaluated. Included therein were investigations of through-hardened and case carburized materials having various OD/ID (wall thickness) ratios and of different material combinations. These efforts had been successfully completed and reported earlier.[3,4]

b) In Tasks IX through XIII, RCF testing of and subsequent metallurgical evaluation of eleven candidate alloys (Phase I) were undertaken. Additionally, the effects of different heat treating processes and additional vacuum melting processes on the RCF life of several selected case carburizing alloys (Phase II) were determined. The results were compared with the standard aviation bearing and gear alloys, VIM-VAR AISI M-50 and VAR AISI 9310, respectively. The work covering the Task IX through XIII (Phase I and II gear materials) has been reported as an interim report.[5]

The purpose of this report is to document the final phase (Phase III) of the contract comprising Tasks XIV and XV. Several of these materials are from the same heats of material and melting process as gears used in full-scale spur gear tests to be performed by NASA. This phase includes RCF testing and metallurgical evaluation of Phase III materials as follows:

PHASE III TESTS

Test Series	Melting Process	Test Material	Remarks
AG	VIM-VAR[a]	AISI M-50	replaces VAR Nitralloy[b]
AH	AM[c]	CBS600[d]	-
AI	VAR	CBS1000M[d]	-
AJ	VAR	Vasco X-2[d]	tempered at 316°C (600°F)
AK	VAR	Vasco X-2[d]	tempered at 510°C (1000°F)
AL	VAR	Vasco X-2[d]	tempered at 316°C (600°F)
AM	VAR	Vasco X-2[d]	tempered at 316°C (600°F), shot peened
AN	VAR	VascoMax 350	-
AO	VAR	Vasco Matrix II	-

(a) - Vacuum induction melted (VIM) followed by vacuum arc remelted (VAR).

(b) - Initially scheduled materials replaced due to unsatisfactory specimens or unavailability of specimens.

(c) - Air melted.

(d) - Test materials from same heats of material or gears to be tested by NASA.

PHASE III TESTS (Continued)

Test Series	Melting Process	Test Material	Remarks
AP	VAR	AISI M-50	-
AQ	VAR	AISI 9310	replaces REX 729[b]
AR	VIM-VAR	AISI 9310	-
AS	VAR	EX00014	-
AT	VAR	EX00053	-
AU	VIM-VAR	AISI M-50	gold-plated
AV	VIM-VAR	AISI M-50	chrome-plated

(b) - Initially scheduled materials replaced due to unsatisfactory specimens or unavailability of specimens.

II. EXPERIMENTAL

Sixteen Phase III materials were tested in the General Electric rolling contact (RC) fatigue rigs. The chemical compositions for Phase III materials are given in Appendix A. The effects of tempering, vacuum melting, shot peening, and gold and chrome plating on rolling contact fatigue were evaluated. Metallurgical analyses were made before and after the RC rig tests. Test data were analyzed statistically using the Weibull distribution function.

a) Rolling Contact Fatigue Testing

The Rolling Contact (RC) fatigue test rigs have been used since 1957 to evaluate bearing/gear alloys and materials/lubricants interactions. Photographs of RC rigs are shown in Figures 1 and 2. The detailed testing procedure is described elsewhere.[6]

Experimental test conditions used in RC rigs were as follows:

Maximum Hertzian Stress:	4,826 MPa (700 ksi)
Rolling Speed:	6.23 m/sec (245 in/sec)
Lubricant:	MIL-L-7808
Temperature:	Room-ambient

Load is applied to produce Hertzian contact stress by closing two identical seven-inch diameter rollers with a crown radius of 6.35 mm (0.25 in) against a cylindrical test bar 76.2 mm(3 in) long, 9.525 mm (0.375 in) diameter. Figure 3 shows the drawing for specimen geometry and specification. The rollers are made of CVM AISI M-50, per AMS 6490, with a hardness of HRC 63±1.

Stauffer Jet I brand (MIL-L-7808) oil is supplied to the contacting surfaces by drip feeding approximately 20 drops per minute. Physical property data of the lubricant are given in Appendix B.

Test bars and rollers were finish ground to surface roughness of 6-8 μin (0.15 - 0.20 μm) rms and 8-12 μin (0.20 - 0.30 μm) rms, respectively. The composite surface roughness, σ_c is estimated using the relationship:

$$\sigma_c = \left(\sigma_1^2 + \sigma_2^2\right)^{1/2}$$

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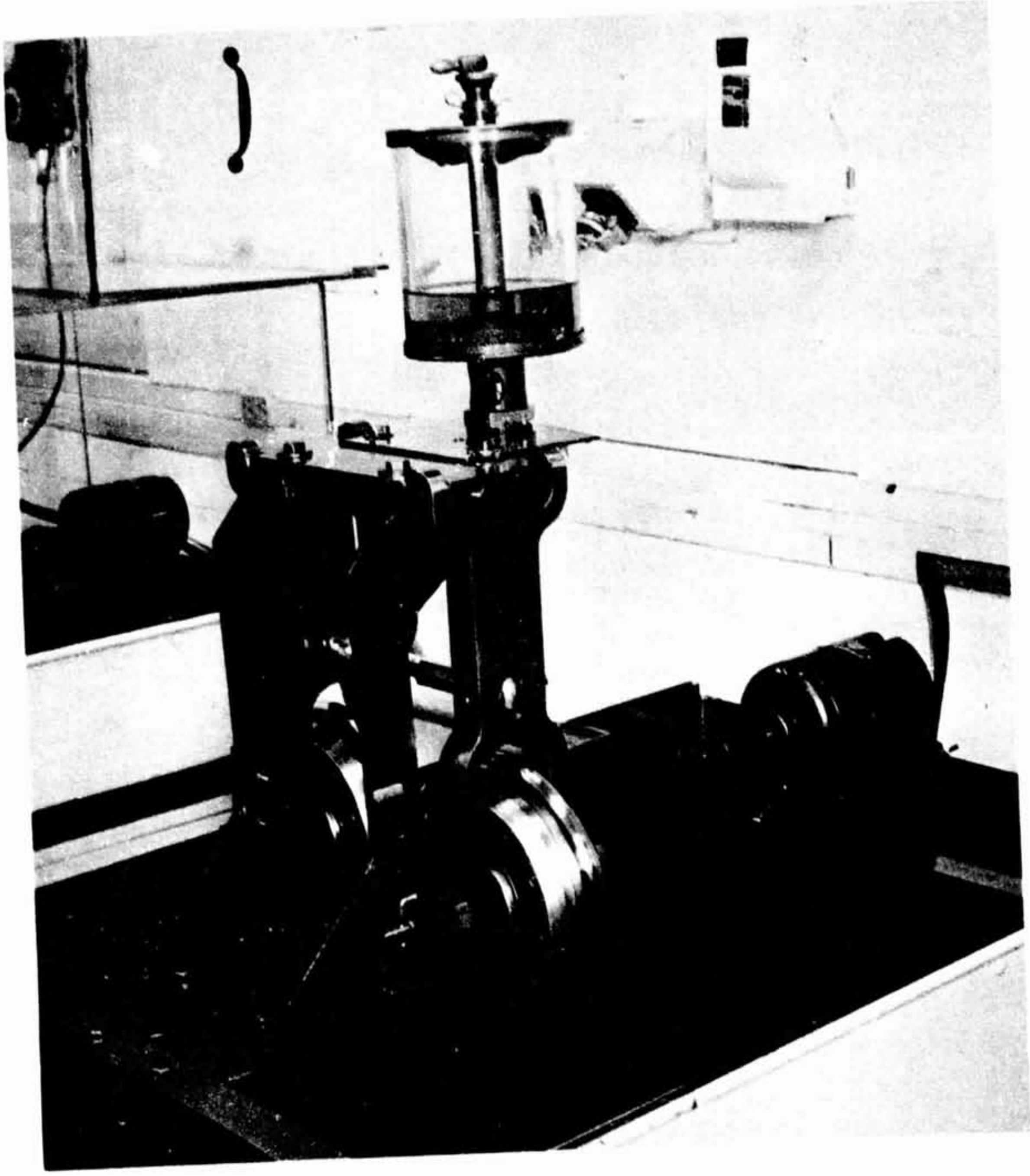


Figure 1. Overview, GE RC Rig.

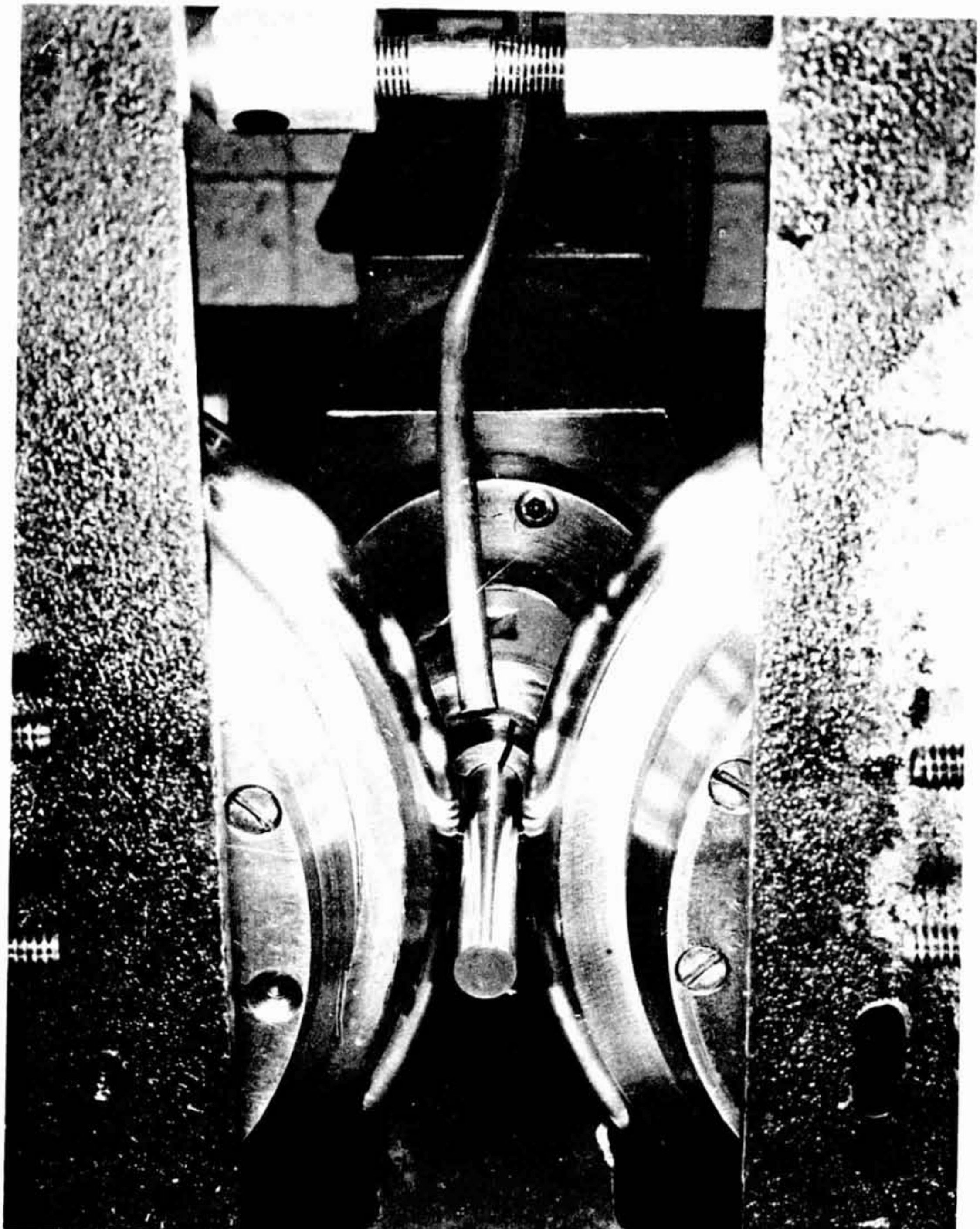


Figure 2. Closeup, Specimen and Roller Geometry in Rig.

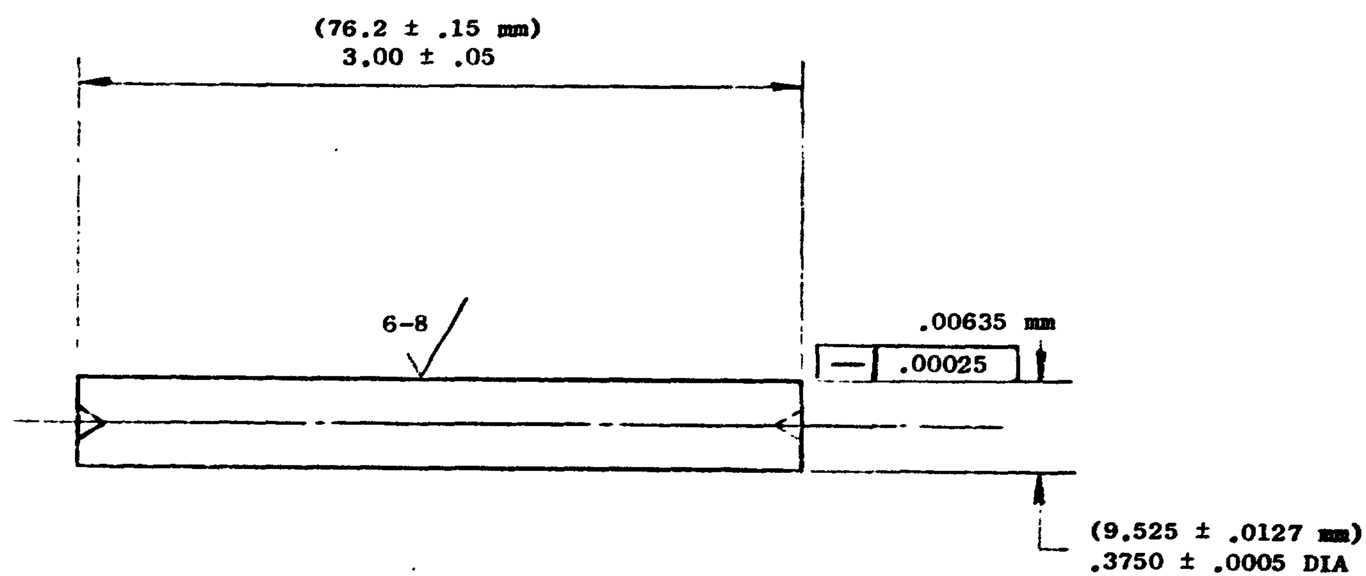


Figure 3. RC Rig Specimen Geometry and Specification.

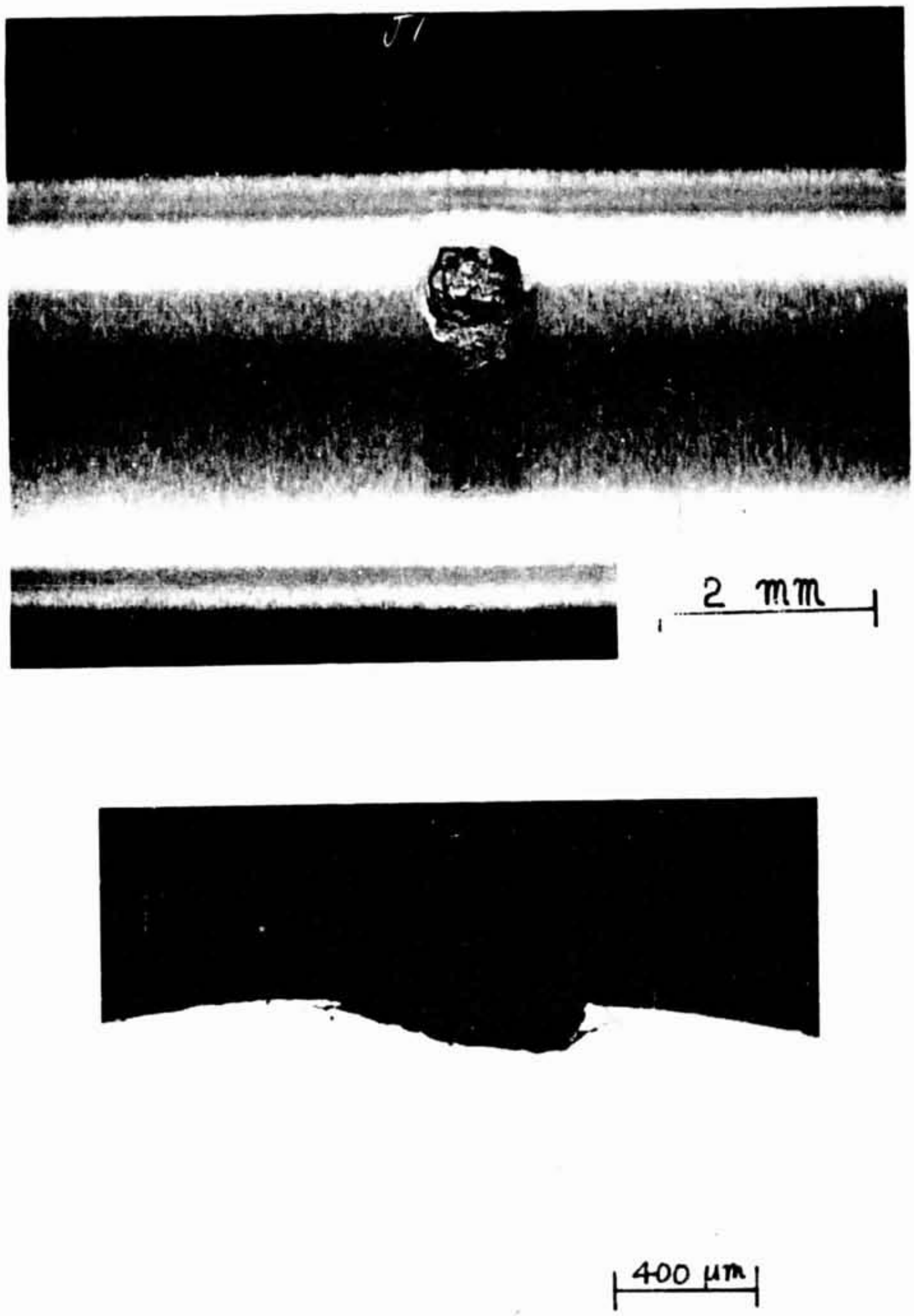


Figure 4. Typical Rolling Contact Fatigue Failure in CBS 600.

where σ_1 and σ_2 are the surface roughnesses of the mating parts. The surface roughnesses of test bars and a new set of rollers rapidly change to smoother surfaces after a short period of testing time, while the surface roughnesses degrade gradually as the testing time is increased. Consequently, the composite surface roughness is estimated to be 10 - 25 μin (0.25 - 0.64 μm).

Cheng's formula[7] was used to calculate the minimum oil film thickness, h_{min}. Based on viscosity of the lubricant at 38°C (100°F), the film thickness is 8.3 μin (0.21 mm). Therefore, the specific film thickness ratio = $\frac{h_{min}}{\sigma_c}$ is considered to be in partial elastohydrodynamic lubrication regime, typical of bearing and gear applications.

Failure mode observed in RCF testing was of classical subsurface initiated fatigue spalling or pitting, characteristic of that observed in bearings and gears. A rolling fatigue failure of CBS600 is shown in Figure 4 as an example.

b) Metallurgical Evaluation of Test Materials

Hardness in Rockwell C (HRC) converted from Rockwell 15-N was measured on each test bar before RCF testing. Microhardness measurements were made to determine the effective case depths of the case hardened materials. The effective case depth is defined as the depth below surface at which hardness is HRC 58. Conventional optical metallographic specimens were prepared to examine the microstructure before and after the testing.

Volume percent of retained austenite was determined on the surface of test specimens with an X-ray metallographic technique. The technique involves the measurement of X-ray peaks intensity diffracted from (200) planes of austenite and martensite structures. Chromium K_α radiation at 50 kv was used to obtain the X-ray diffracted peaks.

c) Fatigue Data Analysis

Rolling contact fatigue data were analyzed in the Weibull distribution function and statistically considered in a manner suggested by Johnson.[8] The fatigue life in number of stress cycles as abscissa versus the statistical cumulative failures as ordinate were plotted in the Weibull probability graph. B-10 or B-50 lives are defined here as the number of cycles where 10% or 50%, respectively, of the test population are expected to fail in spalling fatigue. Since early failures in contact fatigue are much more significant in engineering practice, B-10 life was used as a criterion to evaluate the rolling contact fatigue life performance.

III. RESULTS AND DISCUSSION

Rolling contact fatigue test results of Phase III test series are given in Appendix C. Corresponding Weibull plots are also included in Appendix D. A summary of test results and metallurgical analyses on Phase III materials are shown in Appendix E. Data for VIM-VAR AISI M-50 and VAR AISI 9310 are included in the Appendix E as a baseline. AISI M-50 data are based on more than 250 RCF tests with 12 different heats which were heat treated to HRC 63±1.

For convenience, this chapter is categorized according to materials.

a) AISI M-50

Four test series were done in Phase III, as follows:

Test Series	Melting Process	Remarks
AG	VIM-VAR	-
AP	VAR	-
AU	VIM-VAR	gold plated
AV	VIM-VAR	chrome plated

Chemical composition for AISI M-50 test series is given in Table 1. Heat treating process for AISI M-50 test specimens is described in Table 2.

Ion plating of VIM-VAR AISI M-50 test specimens with chrome and gold were performed in a vacuum chamber. Electrical potential between cathode and anode was between 3000 and 5000 volts DC. Final plating thickness was controlled to be 1800±300 angstroms (7.1±1.2 μ in.) on both specimens. Purity of the gold and chrome anodes were 99.9999% and 99.999%, respectively.

Table 3 shows a summary of RCF test results and metallurgical analyses of AISI M-50. Weibull plots are shown in Figure 5. B-10 lives are shown as a histogram in Figure 6.

Optical microstructures of VAR M-50 (test series AP) and VIM-VAR M-50 (test series AG, AU and AV) are shown in Figures 7 and 8. No noticeable differences were found except the VAR AISI M-50 specimens (Figure 8-a) has fewer carbides than the VIM-VAR AISI M-50 (Figure 8-b). Retained austenite was not detected with X-ray diffraction technique in any of the AISI M-50 specimens. This means that the volume percent

TABLE 1

CHEMICAL COMPOSITION OF AISI M-50

Test Series	Melting Process	Plating	Alloying Element, Percent by Weight (Balance Fe)											
			C	Sn	Mn	S	P	W	Cr	V	Mo	Co	Ni	Cu
AG	VIM-VAR	None	0.82	0.24	0.26	0.008	0.010	0.02	4.16	1.06	4.32	0.03	0.08	0.08
AP	VAR	None	0.80	0.22	0.24	0.005	0.006	0.04	3.98	0.98	4.18	0.05	0.07	0.06
AU	VIM-VAR	gold plated	same as AG											
AV	VIM-VAR	chrome plated	same as AG											

TABLE 2

HEAT TREATING PROCESS FOR AISI M-50

Heat Treating	Test Series AG VIM-VAR	Test Series AP VAR	Test Series AU VIM-VAR	Test Series AV VIM-VAR
Preheat	816°C (1500°F) in salt for 15 minutes.	816°C (1500°F) in salt for 30 minutes.	same as Test Series AG	same as Test Series AG
Austenitize	1110/1116°C (2030/2040°F) in salt for 5 minutes.	1113°C (2035°F) in salt for 6 minutes.		
Quench	579°C (1075°F) for 10 minutes, air cool to 66°C (150°F) or lower.	574°C (1065°F) for 20 minutes, air cool.		
Temper	548°C (1020°F) for 2 hours, air cool.	552°C (1025°F) for 2 hours, air cool.		
Deep Freeze	-73°C (-100°F) for 2 hours, air warm.	-73°C (-100°F) for 2 hours.		
Temper	548°C (1020°F) for 2 hours, air cool.	552°C (1025°F) for 2 hours, air cool.		
Plating	--	--	gold plated	chrome plated

TABLE 3

SUMMARY OF TEST RESULTS AND METALLURGICAL CHARACTERISTICS OF AISI M-50

Test Series	Melting Process	B-10 Life, x 10^6 Cycles	B-10 Life, x 10^6 Cycles	Weibull Slope	Failure* Index	Hardness HkC	Retained Austenite, %	Remarks
AG	VIM-VAR	3.34	7.77	2.23	27/27	63.0	N.D.**	-
AP	VAR	2.46	4.01	3.85	20/20	60.6	N.D.	-
AU	VIM-VAR	4.21	8.88	2.52	10/10	63.0	N.D.	gold plated
AV	VIM-VAR	2.28	10.66	1.22	10/10	63.0	N.D.	chrome plated
Base-line	VIM-VAR	3.80	6.30	3.30	250/250	63.0	N.D.	12 heats were used

Test Conditions:

Max. Hz Stress: 4,826 MPa (700 ksi)
Speed: 6.23 m/sec (245 in/sec)
Lubricant: MIL-L-7808
Temperature: Room-ambient

*Number of tests to failure out of total number of tests.

**Not detected by X-ray diffraction technique.

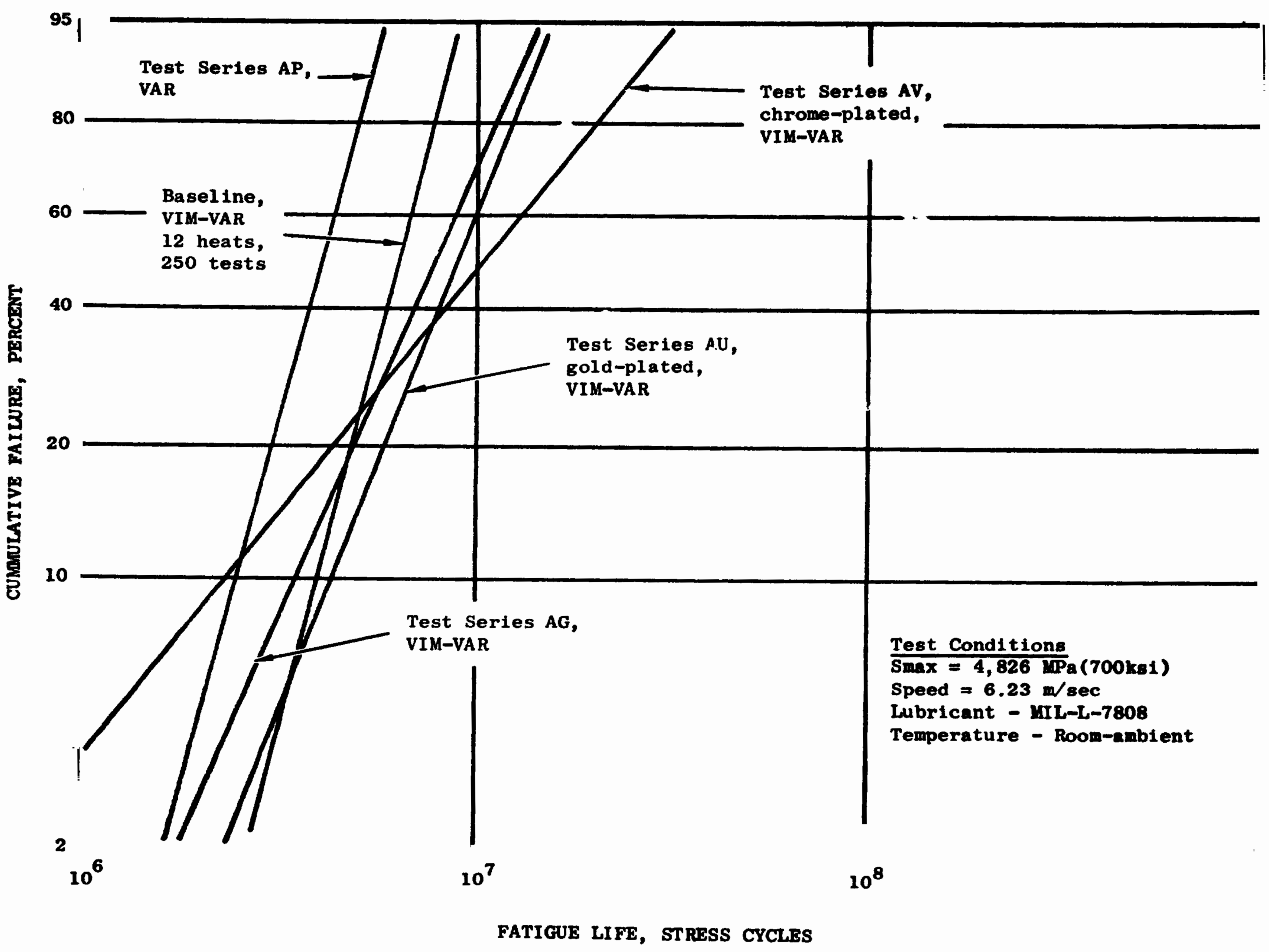


Figure 5. Fatigue Life Comparison of AISI M-50.

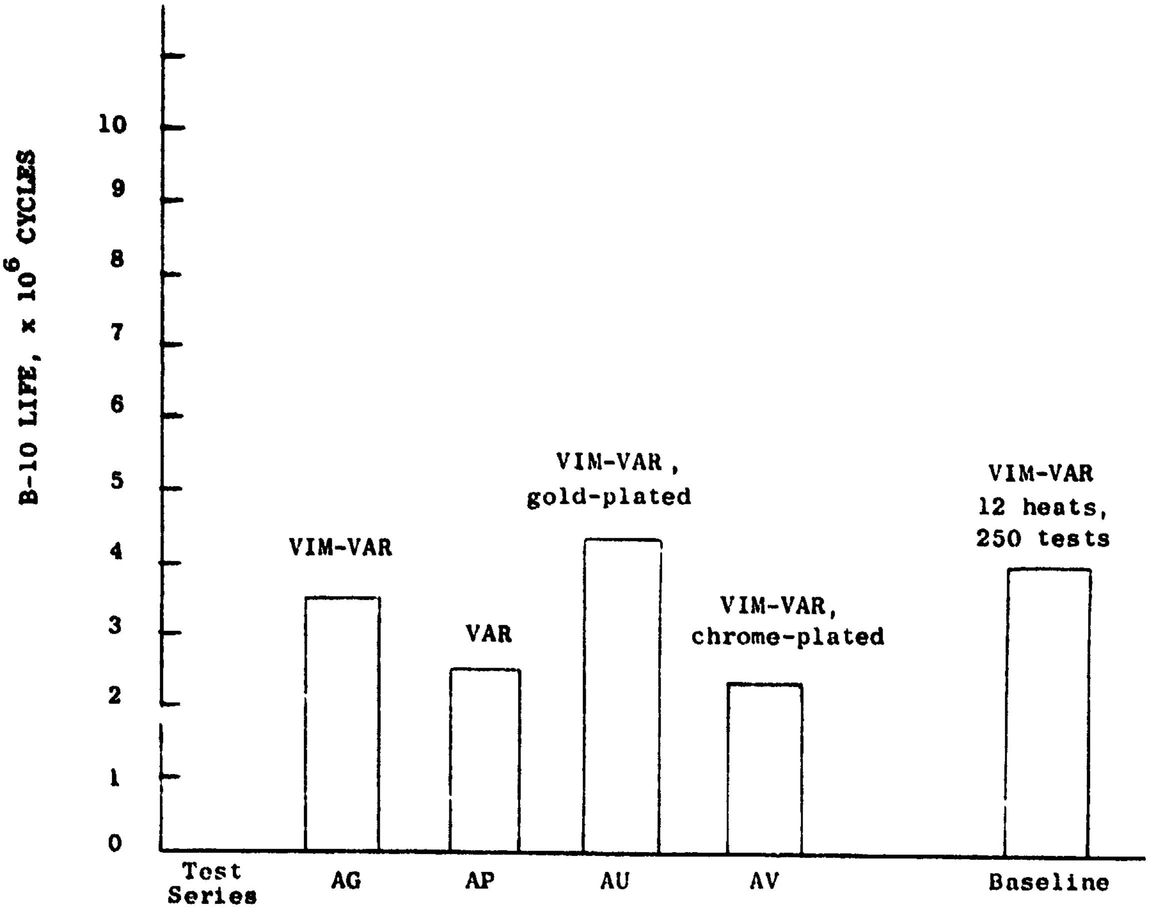
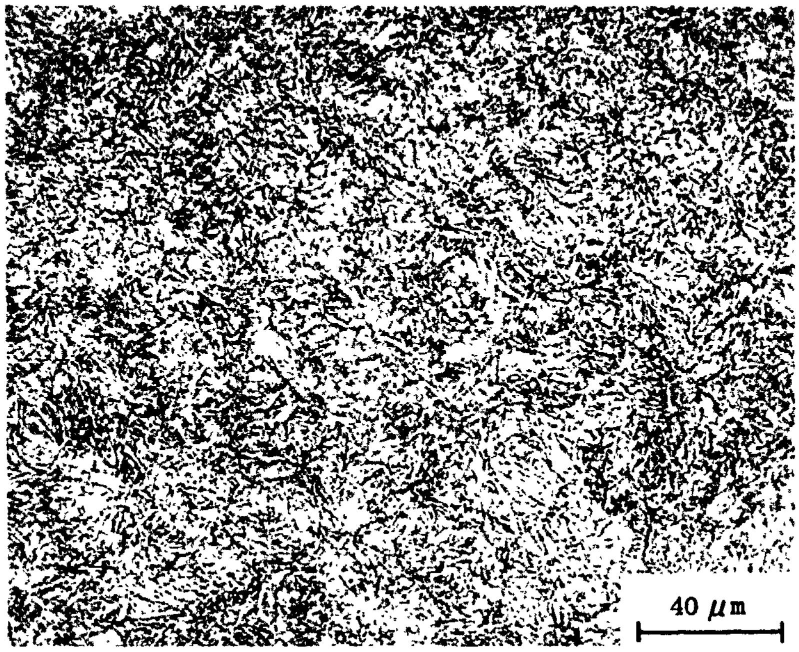
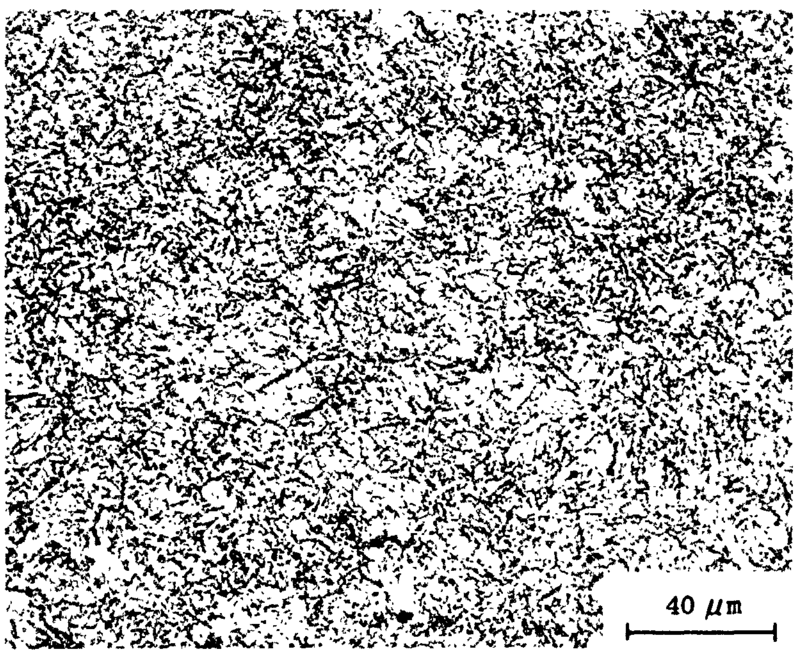


Figure 6. B-10 Fatigue Life of AISI M-50.

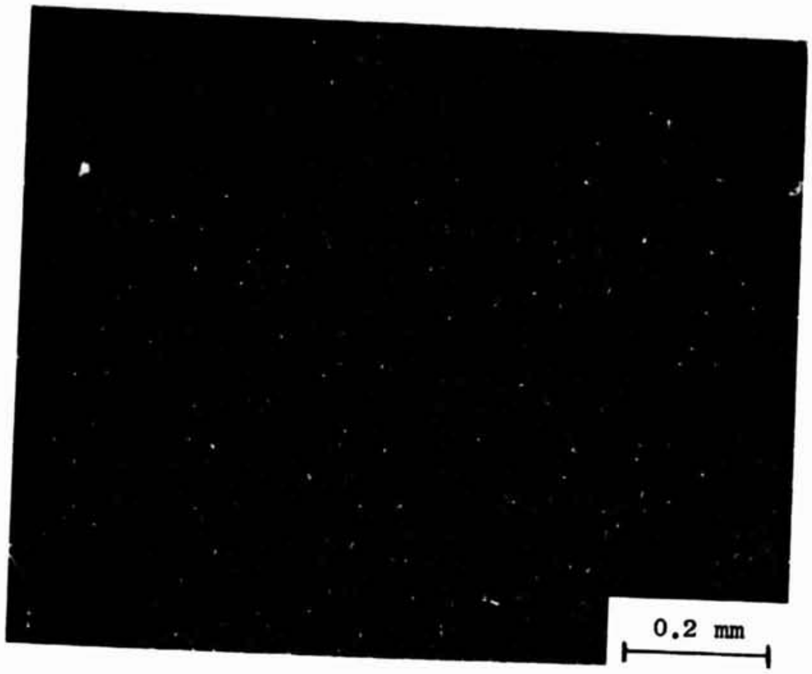


(a)



(b)

Figure 7. Optical Microstructure of AISI M-50, Nital Etch:
(a) VAR AISI M-50 (Test Series AP) and
(b) VIM-VAR AISI M-50 (Test Series AG, AU & AV)



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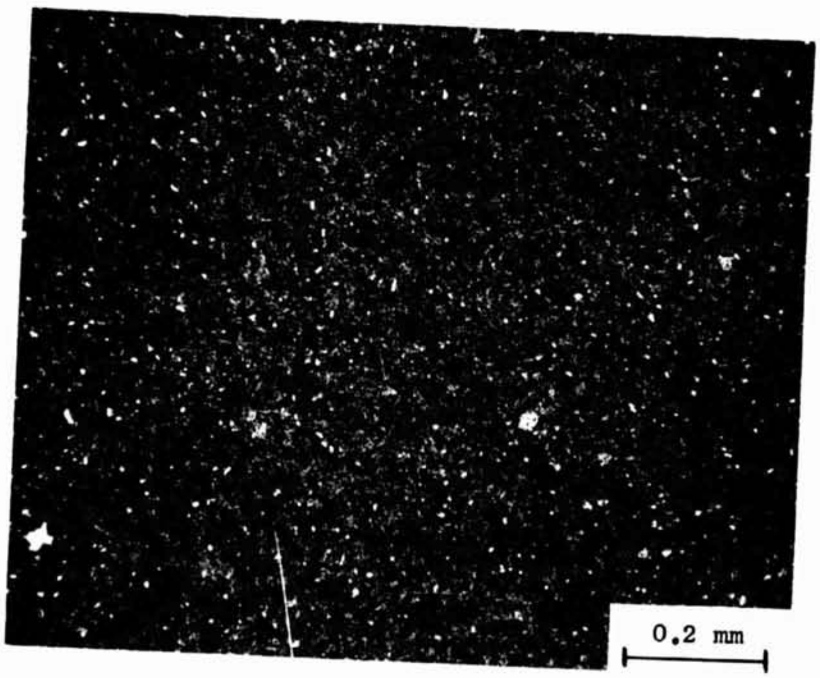
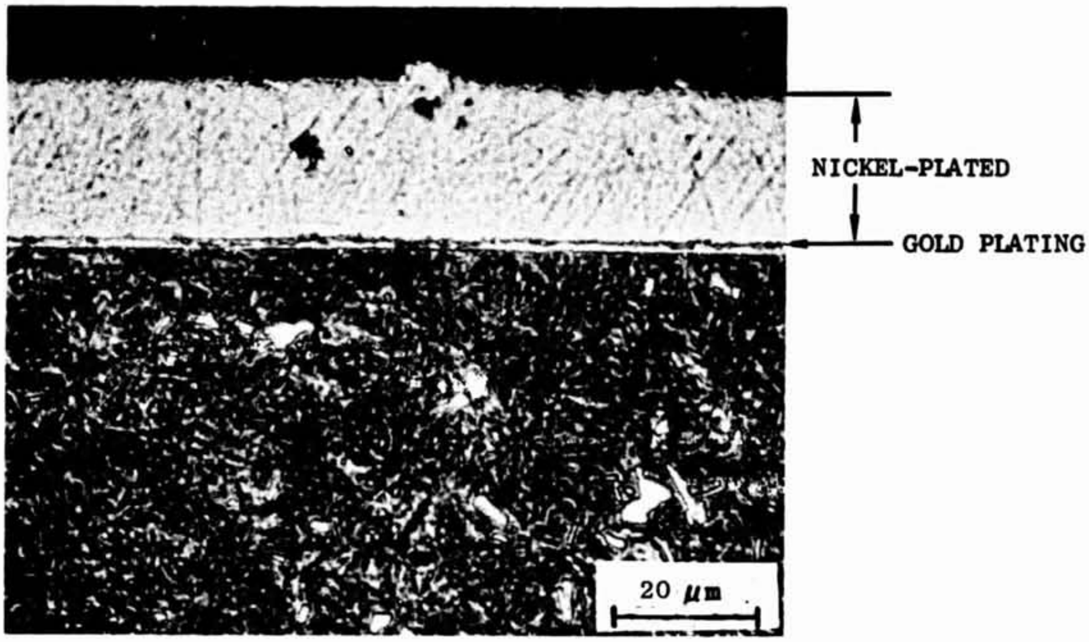
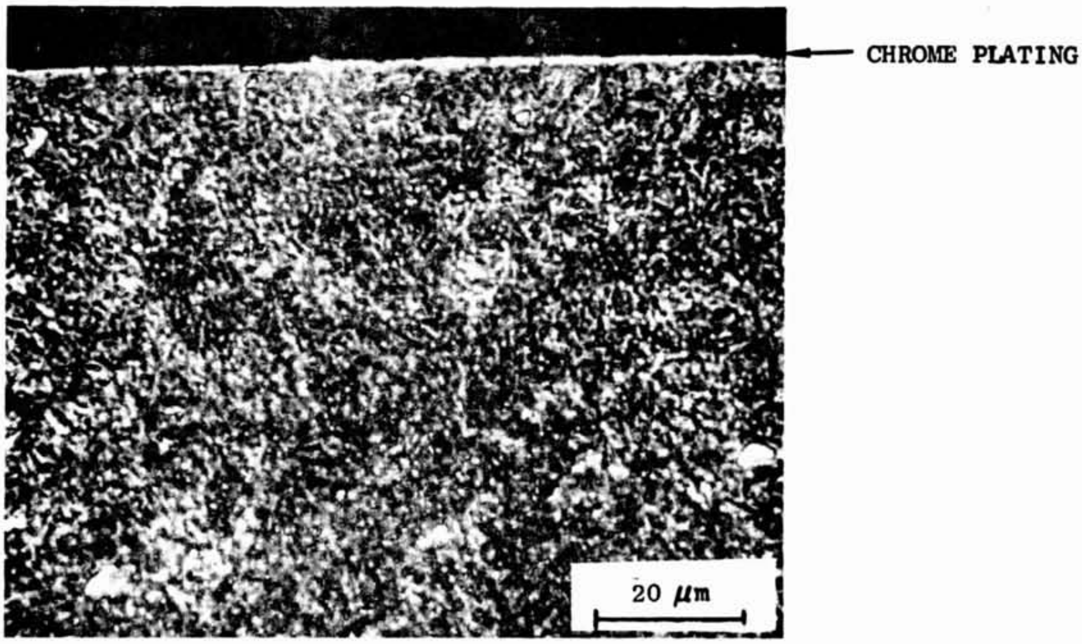


(b)

Figure 8. Optical Micrographs Showing Carbides in AISI M-50, Nital Etch:
(a) VAR AISI M-50 (Test Series AP) and
(b) VIM-VAR AISI M-50 (Test Series AG, AU & AV)



(a)



(b)

Figure 9. Optical Microstructure of AISI M-50, 3% Nital Etch:
(a) Gold-plated VIM-VAR AISI M-50 (Test Series AU) and
(b) Chrome-plated VIM-VAR AISI M-50 (Test Series AV).

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of retained austenite was below 2%. Test series AG (VIM-VAR AISI M-50) shows B-10 life of $3.34x10^6$ cycles, being close to that of baseline data for VIM-VAR AISI M-50. VAR AISI M-50 (test series AP) has lower RCF life than double vacuum processed AISI M-50 (test AG and baseline data). However, the difference is not significant. This appears to be contrary to previous general experience where VIM-VAR AISI M-50 has approximately twice the RCF life of VAR AISI M-50.

Both gold and chrome platings were observed to be removed shortly after initial testing period. Figure 9 shows the plating of untested specimens. A gold plated bar was nickel plated to preserve the plating for optical microscopy (Figure 9-a). Failure modes in plated specimens were identical to those of other nonplated specimens. The detrimental effect of chrome plating may be from hard particles generated during the initial testing time. Present results indicate no improvement in RCF life with chrome plating. Again, the difference is not statistically meaningful.

b) AISI 9310

Chemical compositions, heat treating processes and a summary of RCF test results and metallurgical characteristics for the AISI 9310 test series in Phases I, II and III are provided in Tables 4, 5, and 6, respectively. Figure 10 shows corresponding Weibull plots of test results. B-10 lives are indicated as a bar chart in Figure 11. As indicated in Table 5, test series AA and baseline test were heat treated at the same time under identical conditions. The same is true for test series AQ and AR. Microstructures for test series AQ and AR are shown in Figures 12 and 13, respectively.

Contrary to Phase II study, it was indicated from Weibull analysis of data, the double vacuum processed AISI 9310 (VIM-VAR, test series AR) had a significantly greater B-10 life than the single vacuum melted AISI 9310 (VAR, test series AQ). However, the data for these two test series indicates that the B-10 lives are comparable when the first five or six early failures are considered for Weibull analysis. (See Figures 43 and 44 in Appendix D.) This should be clarified in future studies.

Volume percent retained austenite was varied from 7.7% to 20.1%. It may be resultant from higher austenitizing temperatures employed (843°C, 857°C (1550°F, 1575°F)) than recommended hardening temperatures by Aerospace industry for AISI 9310 (816°C (1500°F)).

Higher amount of carbon absorbed in metal matrix during higher temperature austenitizing retards martensitic transformation during cooling. This results in retaining more austenite after the transformation.

TABLE 4

CHEMICAL COMPOSITION OF AISI 9310

Phase	Test Series	Test Materials	C	Si	Mn	S	P	Cr	Mo	Ni	Cu
			Alloying Element, Percent by Weight (Balance Fe)								
I	X	AISI 9310 (VAR)	0.07	0.23	0.63	0.007	0.007	1.32	0.13	3.24	0.10
II	AA	AISI 9310 (VIM-VAR)	0.11	0.31	0.52	0.004	0.006	1.26	0.12	3.24	0.06
	Base-line	AISI 9310 (VAR)	0.11	0.30	0.69	0.002	0.005	1.24	0.11	3.19	0.07
III	AQ	AISI 9310 (VAR)	0.10	0.28	0.54	0.001	0.006	1.18	0.11	3.15	0.06
III	AR	AISI 9310 (VIM-VAR)	0.11	0.32	0.54	0.004	0.005	1.26	0.12	3.16	0.06

TABLE 5

HEAT TREATING PROCESS FOR AISI 9310

Heat Treating	Test Series X (VAR)	Test Series AA (VIM-VAR)	Test Series Baseline	Test Series AQ (VAR)	Test Series AR (VIM-VAR)
Preheat	927°C (1700°F) 15 minutes, air cool to RT	--	--	--	--
Carburize	927°C (1700°F) 6 hours	941°C/968°C (1725°F/1775°F) 12 hours	Same as Test Series AA	899°C (1650°F) 8 hours, air cool to RT	Same as Test Series AQ
Reheat	--	593°C (1100°F) 10 hours, air cool	Same as Test Series AA	649°C (1200°F) 2.5 hours, air cool	Same as Test Series AQ
Austenitize	857°C (1575°F) oil quench	857°C (1575°F) 20 minutes, oil quench	Same as Test Series AA	843°C (1550°F) 2.5 hours, oil quench	Same as Test Series AQ
Deep Freeze	-73°C (-100°F) 3 hours	-73°C (-100°F) 3 hours	Same as Test Series AA	-84°C (-120°F) 3.5 hours	Same as Test Series AQ
Temper	182°C (360°F) 1 hour	182°C (360°F) 1 hour	Same as Test Series AA	177°C (350°F) 2+2 hours	Same as Test Series AQ
Stress Relieve	--	--	--	177°C (350°F) 2 hours, after finish grinding	Same as Test Series AQ

TABLE 6

SUMMARY OF RCF TEST RESULTS AND METALLURGICAL CHARACTERISTICS OF AISI 9310

Test Series	Melting Process	B-10 Life, $\times 10^6$ Cycles	B-50 Life, $\times 10^6$ Cycles	Weibull Slope	Failure[(a)] Index	Effective Case Depth mm (in.)	Case Hardness, HRC	Core Hardness, HRC	Retained Austenite %	Remarks
X	VAR	14.82	61.50	1.32	6/20	0.76 (0.030)	60.4	41.0	20.1	Phase I
AA	VIM-VAR	5.25	10.65	2.66	10/10	0.84 (0.33)	60.2	38.0	8.3	Phase II
Base-line	VAR	4.18	9.43	2.31	10/10	0.84 (0.33)	61.4	38.0	11.2	Heat Treated as AA
AQ	VAR	2.25	10.63	1.21	9/10	0.51 (0.020)	60.9	42.0	16.1	Phase III
AR	VIM-VAR	6.84	15.74	2.26	10/10	0.64 (0.025)	61.0	42.0	7.7	Phase III

(a) - Number of failures out of total number of tests.

Test Conditions

S_{max} (Max. Hz Stress): 4,826 MPa (700 ksi)

Speed: 6.23 m/sec (245 in/sec)

Lubricant: MIL-L-7808

Temperature: Room-ambient

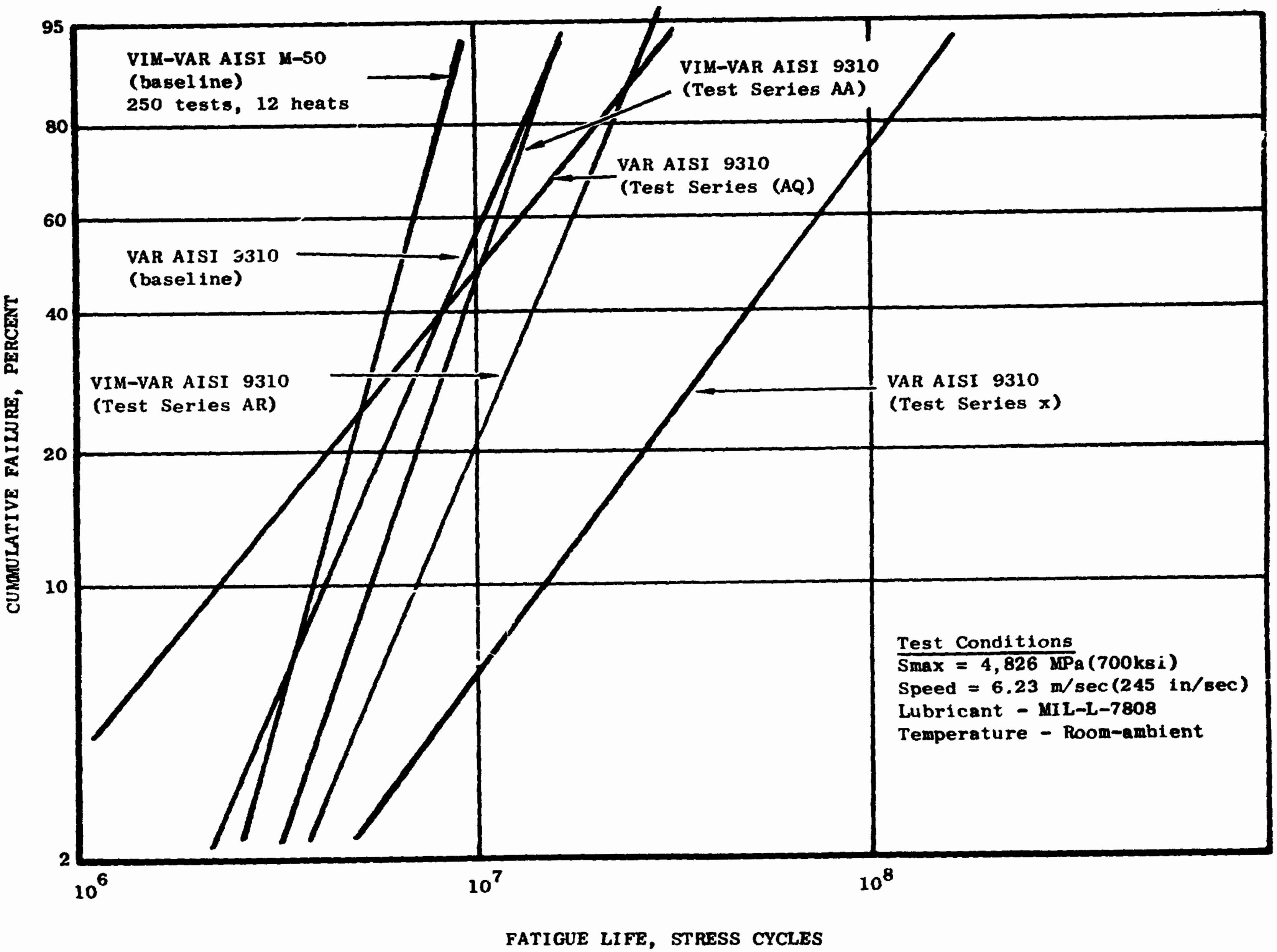


Figure 10. Fatigue Life Comparison of AISI 9310.

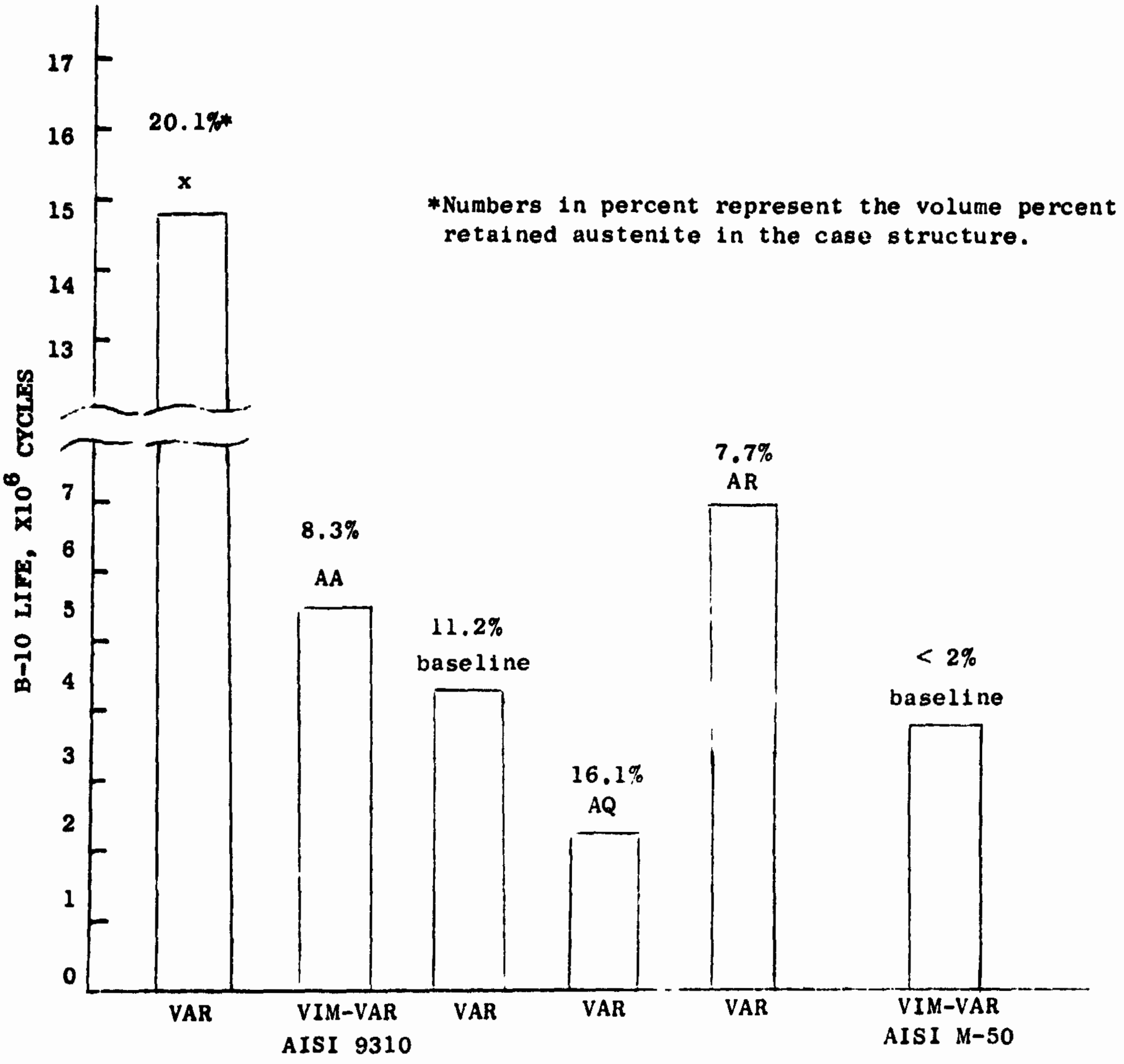
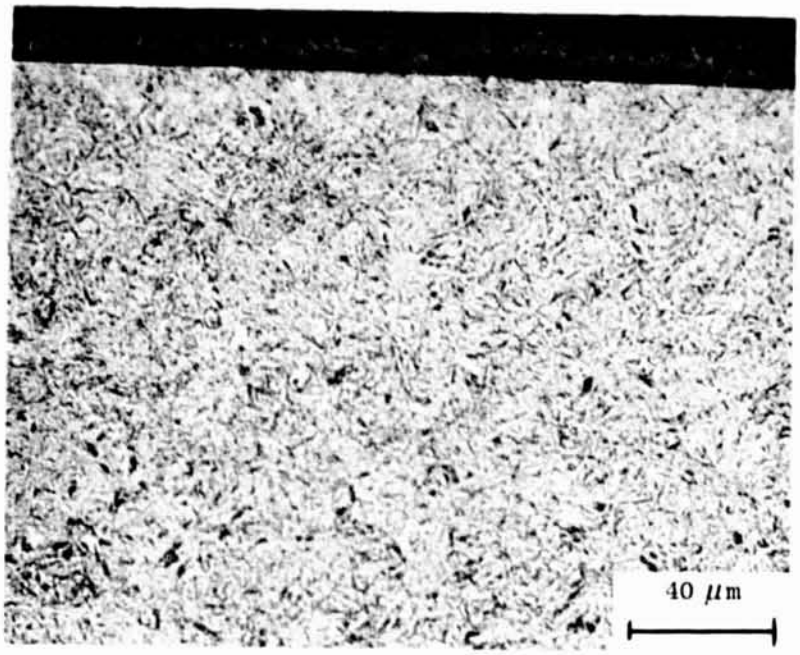
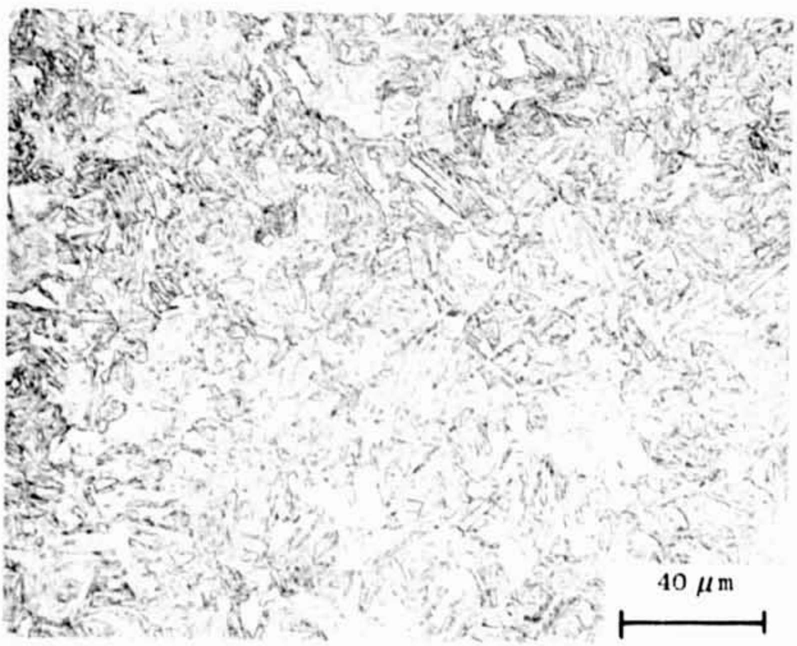


Figure 11. B-10 Fatigue Life Comparision of AISI 9310.



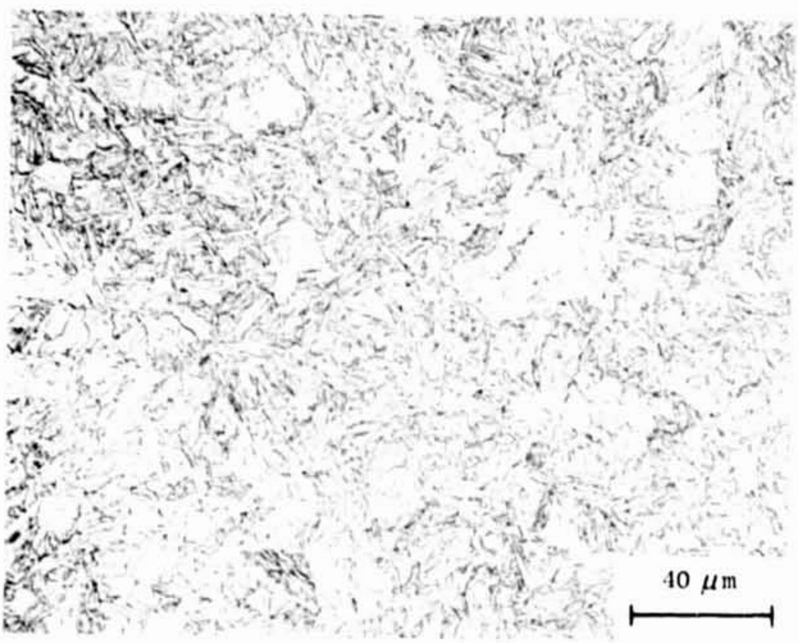
(a)
Case



Core

Figure 12. Optical Microstructure of VAR AISI 9310, Test Series AQ, Nital Etch.

(a)
Case



(b)
Core

Figure 13. Optical Microstructure of VIM-VAR AISI 9310, Test Series AR, Nital Etch.

No conclusive remarks can be made with regards to the effect of retained austenite present in the case structure on RCF. This is because of the results from Phase III. However, it appears that retained austenite must exceed 20% to significantly increase the RCF life in A.SI 9310.

c) EX00014 (Test Series AS)

The specific chemical composition for VAR EX00014 (Test Series AS) was:

C	Si	Mn	S	P	Cr	V	Mo	Ni	Cu	Fe
0.11	0.99	0.36	0.004	0.008	0.99	0.11	0.75	2.96	2.04	Bal.

The heat treating process used for VAR EX00014 is given in Table 7. It was air-hardened after austenitizing at 816°/829°C (1500°/1525°C) for 30 minutes. An advantage of air-hardening is that it is less susceptible to distortion or cracking during heat treating than oil quench hardening, which is more typical for case carburized material. This alloy is said to have greater resistance to tempering than steels such as AISI 9310 or AISI 9310 (+(30 ~ 55)°C).[9]

A summary of the RCF test results and metallurgical evaluation is described in Table 8. Figure 14 shows case and core microstructures of the VAR EX00014 test specimens. It is indicated under the present experimental conditions that RCF performance of VAR EX00014 is equivalent to those of VAR AISI 9310 and of VIM-VAR AISI M-50.

d) CBS600

Chemistry specification for CBS600 is given in Table 9. This alloy was developed for use up to 232°C (450°F).[10] Three heats were employed as follows:

Heat Number	Test Series	Melting Process	Contract Phase
Not known	y	AM*	I
2V6978	AD	VAR	II
2V6978	AE	VAR	II
2V6978	AF	VAR	II
35017	AH	AM*	III

*Air Melted

TABLE 7

HEAT TREATING PROCESS FOR VAR EX00014

(Test Series AS)

1) Preheat to 593°C (1100°F) for 1 hour, air cool.

2) Carburize at 871-927°C (1600 1700°F), furnace cool to 816°C-843°C (1500-1550°F), air cool to room temperature.

3) Austenitize at 816-829°C (1500-1525°F) for 30 minutes, air cool to room temperature.

4) Deep freeze at -73°C (-100°F) for 1 hour.

5) Double-temper at 149°C (300°F) for 2 hours each.

TABLE 8

SUMMARY OF RCF TEST RESULTS AND METALLURGICAL CHARACTERISTICS OF EX00014

Test Series	Materials (Melting Process)	B-10 Life, $\times 10^6$ Cycles	B-50 Life, $\times 10^6$ Cycles	Weibull Slope	Failure[a] Index	Effective Case Depth, mm (in.)	Surface Hardness, HRC	Core Hardness, HRC	Retained Austenite Vol. %
AS	EX00014 (VAR)	3.27	13.85	1.31	10/10	0.51 (0.020)	60.6	42.0	7.7
Base-line	AISI 9310 (VAR)	4.18	9.43	2.31	10/10	0.84 (0.033)	61.4	38.0	11.2
Base-line	AISI M-50 (VIM-VAR)	3.80	6.30	3.30	250/250	--	63.0	--	N.D.[b]

(a) - Number of failures out of total number of tests.

(b) - Not detected.

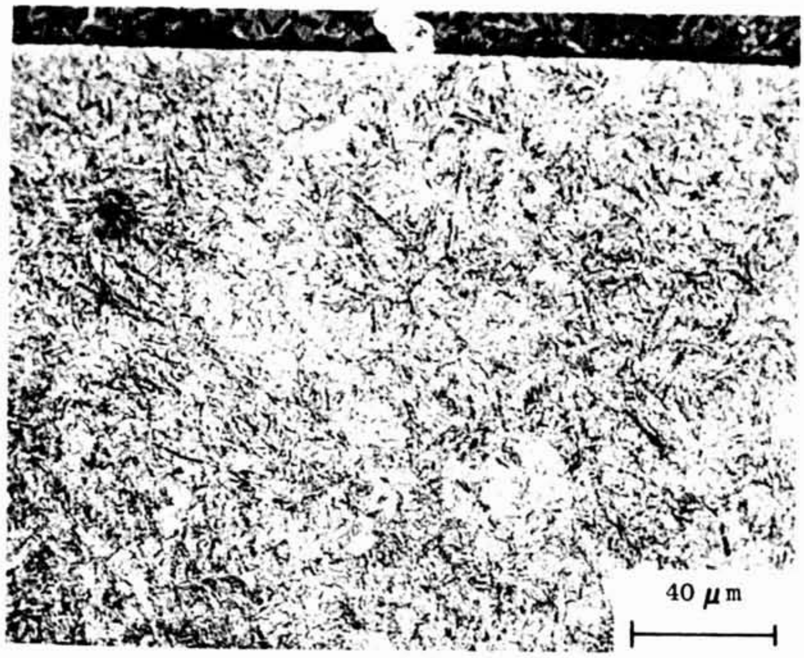
Test Conditions:

Max. Hz Stress (S_{max}): 4,826 MPa (700 ksi)

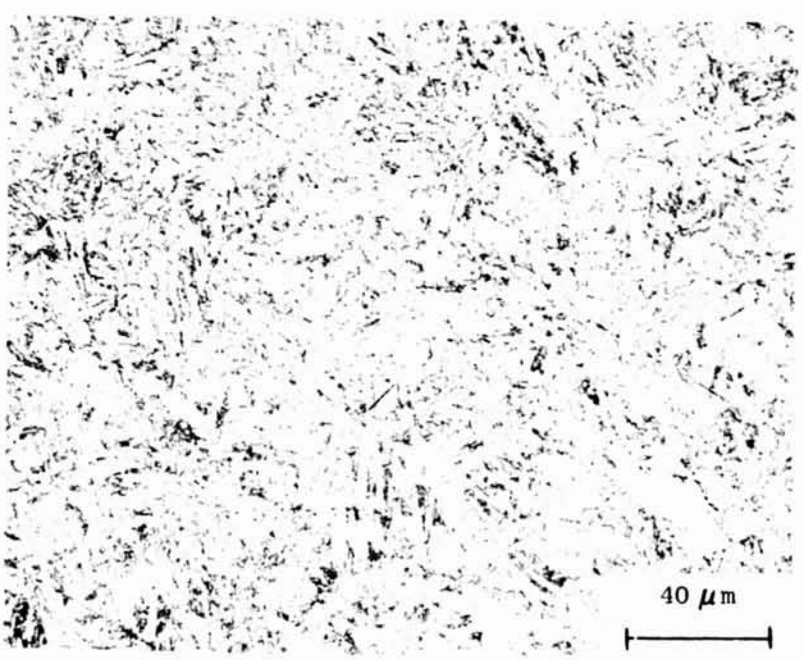
Speed: 6.23 m/sec (245 in/sec)

Lubricant: MIL-L-7808

Temperature: Room-ambient



(a)
Case



(b)
Core

Figure 14. Optical Microstructure of VAR EX00014, Test Series AS, Nital Etch.

TABLE 9

CHEMISTRY SPECIFICATION FOR CBS600

Elements	Weight Percent
Carbon	0.17-0.22
Manganese	0.40-0.70
Sulfur	0.25 Max.
Phosphorus	0.025 Max.
Silicon	0.90-1.25
Chromium	1.25-1.65
Molybdenum	0.90-1.10
Iron	Balance

TABLE 10

CHEMICAL COMPOSITION OF CBS600

(In Weight Percent)

Element	Test Series AD, AE & AF	Test Series AH
Carbon	0.20	0.19
Manganese	0.50	0.61
Phosphorus	0.006	0.007
Sulfur	0.019	0.014
Silicon	1.01	1.05
Chromium	1.54	1.50
Nickel	0.21	0.18
Molybdenum	0.95	0.94
Copper	0.11	-
Iron	Balance	Balance

TABLE 11

HEAT TREATING PROCESS FOR CBS600

Heat Treating	Test Series	Phase I	Phase II	Phase II	Phase II	Phase III
		y	AD	AE	AF	AH
Preheat		593°C (1100°F) 30 minutes	--	--	--	593°C (1100°F) 2 hours
Carburize		927°C (1700°F) 6 hours	941°/968°C (1725°/1775°F) 13 hours, oil	Same as AD	Same as AD	927°C (1700°F) oil quench
Temper		--	621°C (1150°) 4 hours, air cool	Same as AD	Same as AD	593°/649°C (1100°/1200°F) 4 hour
Austenitize		857°C (1575°F) oil quench	829°/843°C (1525°/1550°F) in salt 30 minutes, oil quench	Same as AD	Same as AD	829°/843°C (1525°/1550°F) 25 minutes, oil quench
Deep Freeze		-73°C (-100°F) 3 hours	--	--	-73°C (-100°F) 1 hour	--
Temper		182°C (360°F) 1 hour	182°C (360°F) 2+2 hours	316°C (600°F) 2+2 hours	Same as AE	Same as AE

TABLE 12

SUMMARY OF RCF TEST RESULTS OF CBS600

Test Series	Phase	B-10 Life, $\times 10^6$ Cycles	B-50 Life, $\times 10^6$ Cycles	Weibull Slope	Failure[a] Index
y	I	7.21	16.39	2.29	18/20
AD	II	5.16	11.76	2.29	8/10
AE	II	5.81	11.01	2.95	10/10
AF	II	3.79	9.61	2.02	10/10
AH	III	1.91	7.31	1.40	10/10

(a) - Number of failures out of number of tests.

Test Conditions

S_{max} (Max. Hz Stress):	4,826 MPa (700 ksi)
Speed:	6.23 m/sec (245 in/sec)
Lubricant:	MIL-L-7808
Temperature:	Room-ambient

TABLE 13

METALLURGICAL CASE AND CORE CHARACTERISTICS OF CBS600

Test Series	Phase	Effective Case Depth mm (in.)	Case Hardness HRC	Case Retained Austenite, Vol. %	Core	
					Hardness HRC	Grain Size (ASTM Number)
y	I	0.76 (0.030)	65.0	8.7	43.0	7-8
AD	II	0.84 (0.033)	61.7	4.3	41.0	7-8
AE	II	0.84 (0.033)	60.3	3.4	41.0	7-8
AF	II	0.76 (0.030)	61.6	2.1	41.0	7-8
AH	III	0.76 (0.030)	62.9	22.8	41.0	6-7

Test Conditions

S_{max} = 4,826 MPa (700 ksi)

Speed = 6.23 m/sec (245 in/sec)

Lubricant: MIL-L-7808

Temperature: Room-ambient

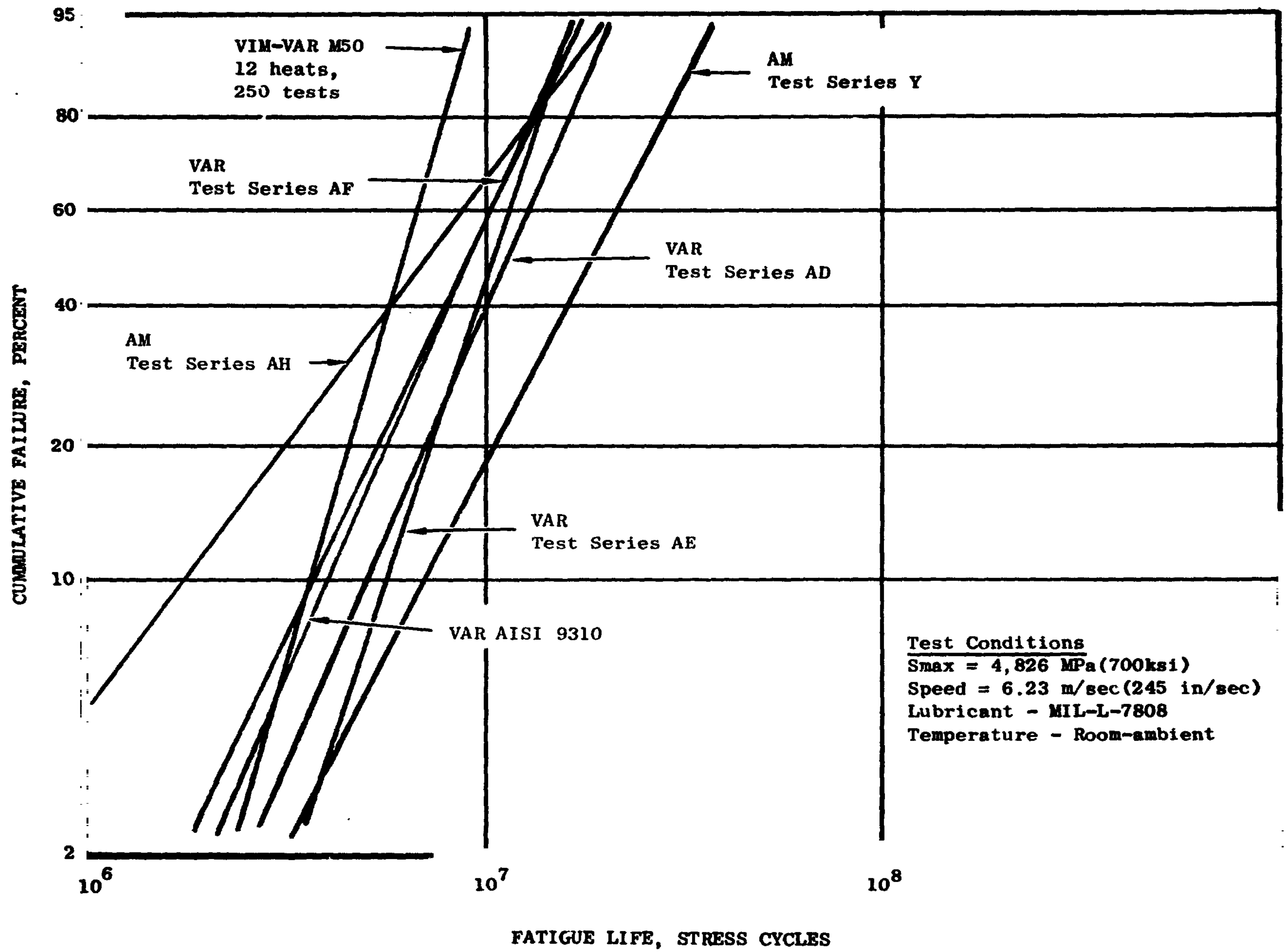


Figure 15. Fatigue Life Comparison of CBS 600

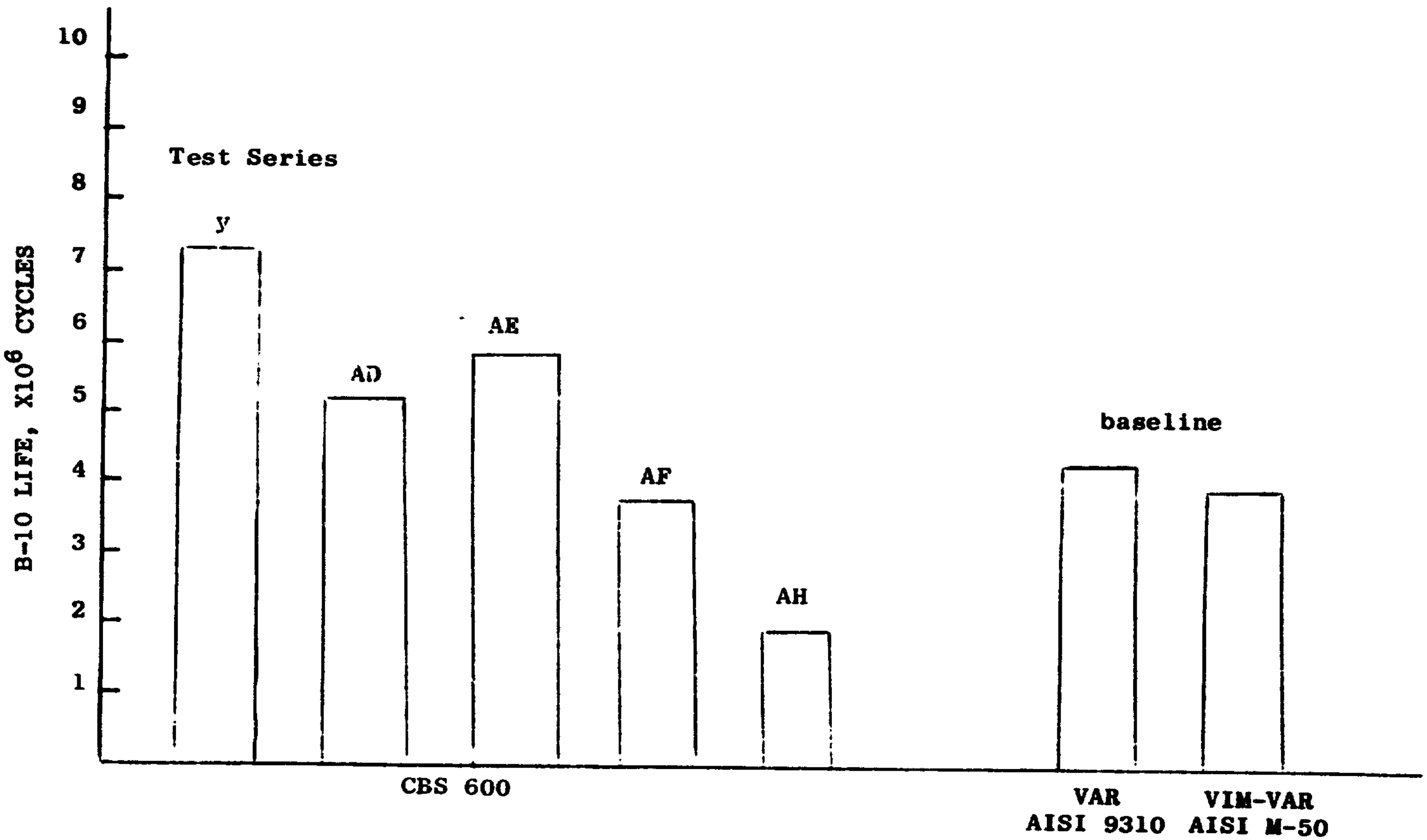
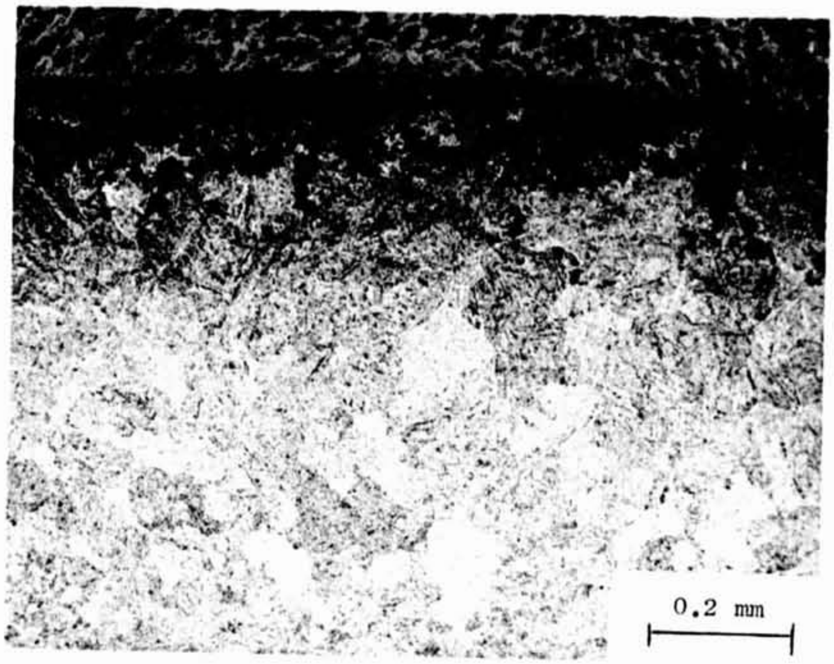
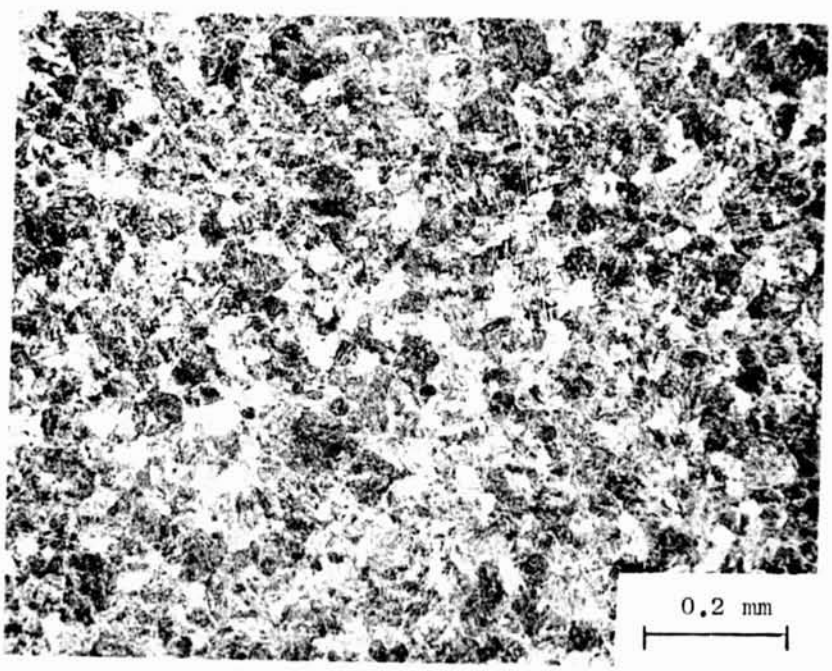


Figure 16. B-10 Fatigue Life Comparisions of CBS 600.

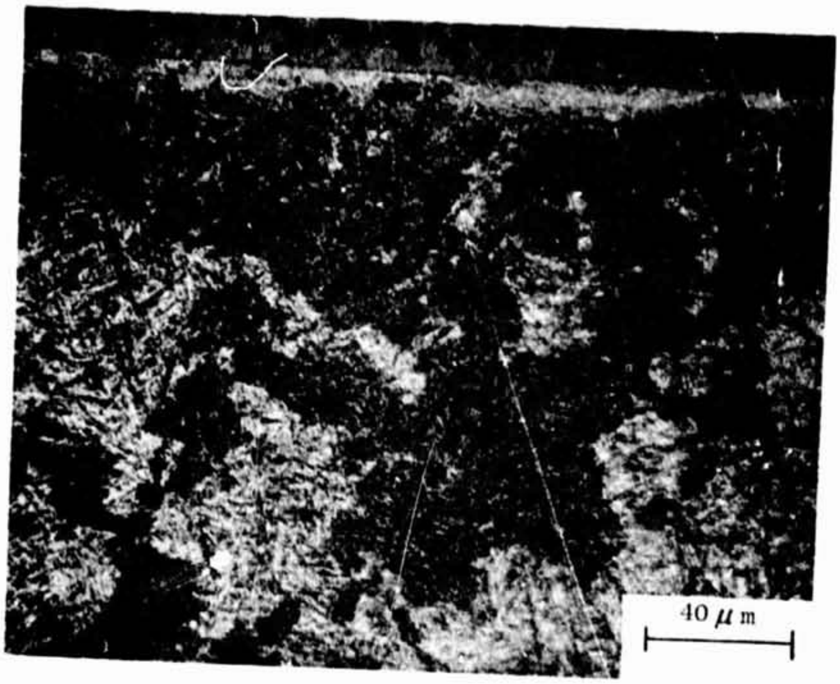


(a)
Case

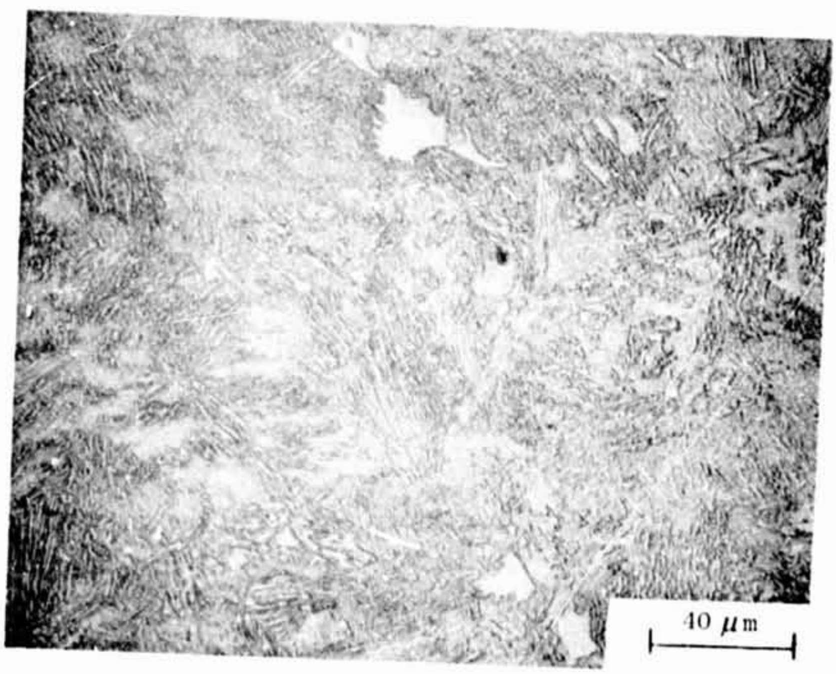


(b)
Core

Figure 17. Optical Microstructure of CBS 600, Test Series AH, Picral Etch.



(a)
Case



(b)
Core

Figure 18. Optical Microstructure of CBS 600, Test Series AH, Nital Etch.

The chemical compositions for Phase III CBS600 (test series AH) and other test series for CBS600 are given in Table 10. Heat treating processes used for CBS600 are summarized in Table 11. A summary of RCF test results and metallurgical analyses on CBS600 are given in Tables 12 and 13, respectively. Corresponding Weibull plots including VAR AISI 9310 and VIM-VAR AISI M-50 are shown in Figure 15. B-10 lives are also plotted as a bar chart in Figure 16.

Optical microstructure of test series AH is shown in Figures 17 and 18. Test series AH was found to have nonuniform, abnormal microstructure with coarse grain size in the core. Preferential etching of case microstructure was observed to occur as indicated by the light and dark areas in Figures 17 and 18. This may be due to some deviation from the specified heat treatment procedure.(11) The deviation appears to be a short hold time (less than five minutes) at austenitizing temperature after slow cooling from carburizing. The case microstructure observed in Figures 17-a and 18-a may have been from the incomplete austenitization of pearlite. The pearlite, an aggregate of ferrite and spherodized carbides, formed during slow cooling after carburizing starting from the grain boundaries. At the same time, blocky ferrite, as shown in Figures 17-b and 18-b, formed at the grain boundaries. The poor fatigue life observed in test series AH may be attributed to the abnormal microstructure.

Results from the Phase I and II, previously reported in Reference (5), indicated no significant effects on RCF performance with different tempering temperatures and with the use of a subzero treatment. The present results suggest that the rolling contact fatigue performance of CBS600 alloy is equivalent to that of VAR AISI 9310 or that of VIM-VAR AISI M-50.

e) EX00053 (Test Series AT)

This experimental alloy, EX00053 for test series AT, has the following chemical specification:

Elements	Weight Percent
C	0.10
Mn	0.35
Si	1.00
Cr	1.00
Ni	2.00
Mo	3.25
Cu	2.00
V	0.10
Fe	Bal.

Specific chemical composition used for test series AT is given in Table 14. Heat treating procedure used for test series AT in this study, is described in Table 15. Test specimens were austenitized at 913°C (1675°F) and then double-tempered at 177°C (350°F). However, manufacturer's data[9] showed that EX00053 can be tempered at 316°C (600°F) to have HRC 61 case hardness and HRC 35 core hardness after carburizing. Rolling contact fatigue test data are included in Appendix C. The test results and metallurgical analyses are summarized in Table 16 where VAR AISI 9310 and VIM-VAR AISI M-50 data are included for comparison. Optical micrographs showing case and core microstructures are shown in Figure 19. Small spherical carbides are seen in the case microstructure.

Present results indicate that RCF strength of VAR EX00053 is inferior to VAR AISI 9310 and VIM-VAR AISI M-50. However, the difference is considered statistically insignificant.

f) CBS1000M (Test Series AI)

CBS1000M was developed for bearing and gear applications at or up to 316°C (600°F).[8] Chemical compositions for CBS1000M, including Phases I and II (test series z, AB and AC) are given in Table 17. Heat treating procedures employed for CBS1000M test specimens are described in Table 18. Specimens for test series z, AC and AI were deep-frozen after being austenitized during heat treating while test series AB specimens were not.

Table 19 summarizes the results of RCF tests and metallurgical analyses of CBS1000M. Microstructures for test series AI (Phase III) are shown in Figure 20. Core microstructure appears coarse. Retained austenite was found to be very low in the case structure for all test series (less than 2%). It was also found that test series z specimens had a nonuniform case depth which varied from 0.43 mm(0.017") to 0.70 mm(0.030"). Case hardness was also varied from HRC 59 to HRC 61, accordingly. Therefore, it was not considered for conclusive evaluation. Test results are shown in Figure 21 where the data for VIM-VAR AISI M-50 and VAR AISI 9310 are included for comparison. B-10 lives are also shown as a bar chart in Figure 22. It was also found that 1100°C (2012°F) austenitizing and 540°C (1000°F) tempering cycles invariably produce the case structure with minimal retained austenite (2%). Deep freezing cycle during heat treating does not appear to improve or degrade RCF performance of CBS1000M.

It is concluded within the range of the present experimental conditions

TABLE 14

CHEMICAL COMPOSITION OF VAR EX00053

(Test Series AT)

	(Weight Percent)
Carbon	0.10
Manganese	0.37
Silicon	0.98
Sulphur	0.006
Phosphorus	0.009
Chromium	1.05
Nickel	2.13
Molybdenum	3.30
Copper	2.07
Vanadium	0.12
Iron	Balance

TABLE 15

HEAT TREATING PROCESS FOR VAR EX00053

(Test Series AT)

1) Preheat to 593°C (1100°F) for 1 hour, air cool.

2) Carburize at 871°/927°C (1600°/1700°F), air cool to room temperature.

3) Austenitize at 913°C (1675°F) for 30 minutes in a protective atmosphere and oil quench.

4) Deep freeze at -73°C (-100°F) for 1 hour.

5) Double-temper at 177°C (350°F) for 2 hours each.

TABLE 16

SUMMARY OF RCF TEST RESULTS AND METALLURGICAL CHARACTERISTICS OF EX00053

Test Series	Test Materials (Melting Process)	B-10 Life, $\times 10^6$ Cycles	B-50 Life, $\times 10^6$ Cycles	Weibull Slope	Failure[a] Index	Effective Case Depth, mm (in.)	Surface Hardness HRC	Core Hardness HRC	Retained Austenite, Vol. %
AT	EX00053 (VAR)	1.95	11.6	1.06	10/10	0.64 (0.025)	62.0	36.0	4.8
Base-line	AISI 9310 (VAR)	4.18	9.43	2.31	10/10	0.84 (0.033)	61.4	38.0	11.2
Base-line	AISI M-50 (VIM-VAR)	3.80	6.30	3.30	250/250	--	63.0	--	N.D.[b]

(a) - Number of failures out of total number of tests.

(b) - Not detected.

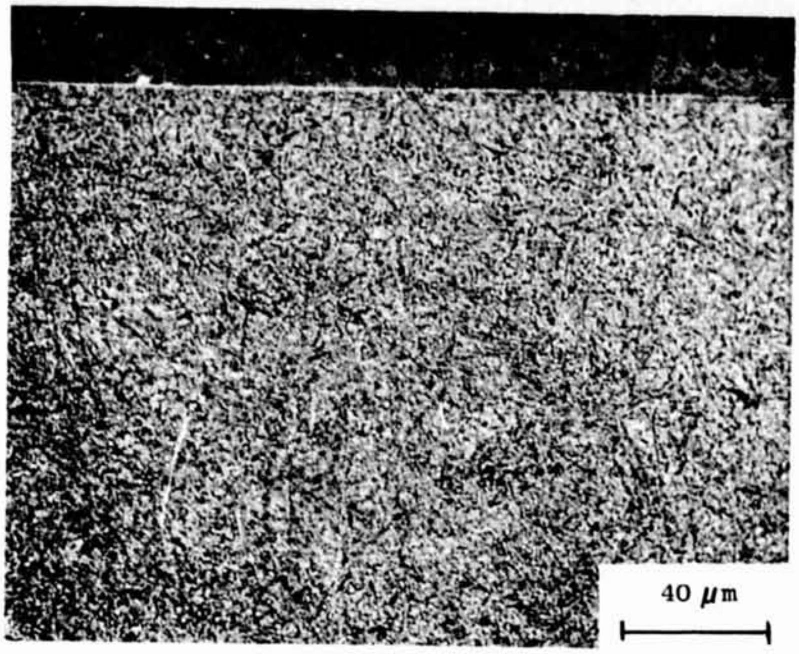
Test Conditions

S_{max}: 4,826 MPa (700 ksi)

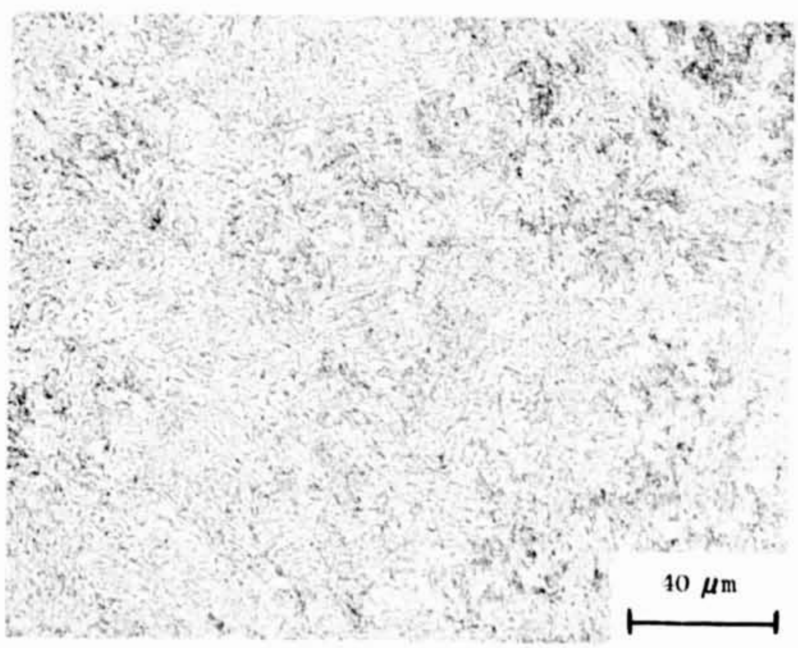
Speed: 6.23 m/sec (245 in/sec)

Lubricant: MIL-L-7808

Temperature: Room-ambient



(a)
Case



(b)
Core

Figure 19. Optical Microstructure of EX00053, Test Series AT, Nital Etch.

TABLE 17

CHEMICAL COMPOSITION OF CBS1000M

Phase	Test Series	C	Si	Alloying Element, Percent by Weight (Balance Fe)									
				Mn	S	P	W	Cr	V	Mo	Co	Ni	Cu
I & II	z, AB & AC	0.135	0.43	0.48	0.019	0.018	--	1.12	0.33	4.77	--	2.94	0.15
III	AI	0.14	0.43	0.48	0.019	0.018	--	1.12	--	4.77	--	2.94	--

TABLE 18

HEAT TREATING PROCESS FOR CBS1000M

Heat Treating	Test Series	Phase I z	Phase II AB	Phase II AC	Phase III AI
Preheat		593°C (1100°F) 2 hours	954°C (1750°F) 1 hour, air cool	988°C (1775°F) 1 hour in vacuum, inert gas quench	593°C (1100°F) 2 hours in air
Carburize		927°C (1700°F) 6 hours	954°C (1750°F) 11 hours	941°C (1725°F) 10 hours, drop to 816°C (1500°F) oil quench	927°C (1700°F) 2 hours
Reheat		788°C (1450°F) 30 minutes, rapid increase to 1107°C (2025°F)	--	816°C (1500°F)	788°C-843°C (1450°F-1550°F) in vacuum fume 15 minutes
Austen-itize		1107°C (2025°F) oil quench	1093°C (2000°F)	1093°C (2000°F) salt quench 552°C (1025°F), air cool	1107°C (2025°F) in vacuum 15 minutes, gas quench
Temper		--	--	371°C (700°F) 1 hour	.
Deep Freeze		-73°C (-100°F) 3 hours	--	-73°C (-100°F) 1 hour	-73°C ~ -84°C (-100°F ~ -120°F) 1 hour
Temper		566°C (1050°F) 2+2+2 hours	538°C (1000°F) 2+2+2 hours	538°C (1000°F) 2+2+2 hours	538°C (1000°F) 2+2+2 hours

TABLE 19

SUMMARY OF RCF TEST RESULTS AND METALLURGICAL CHARACTERISTICS OF CBS1000M

Test Series	B-10 Life, $\times 10^6$ Cycles	B-50 Life, $\times 10^6$ Cycles	Weibull Slope	Failure Index[a]	Effective Case Depth mm (in)	Case Hardness HRC	Core Hardness HRC	Retained Austenite Vol. %
z[b]	1.00	1.99	2.73	20/20	0.43 (0.017)– 0.75 (0.030)	59-61	45.0	N.D.[c]
AB	2.71	6.22	2.27	10/10	1.09 (0.043)	61.6	47.0	1.7
AC	2.11	4.05	2.89	10/10	0.76 (0.030)	60.9	47.0	0.4
AI	2.08	4.36	2.55	10/10	0.76 (0.030)	60.5	41.0	N.D.

(a) - Number of failures out of total number of tests.

(b) - Nonuniform and insufficient case depth.

(c) - Not detected.

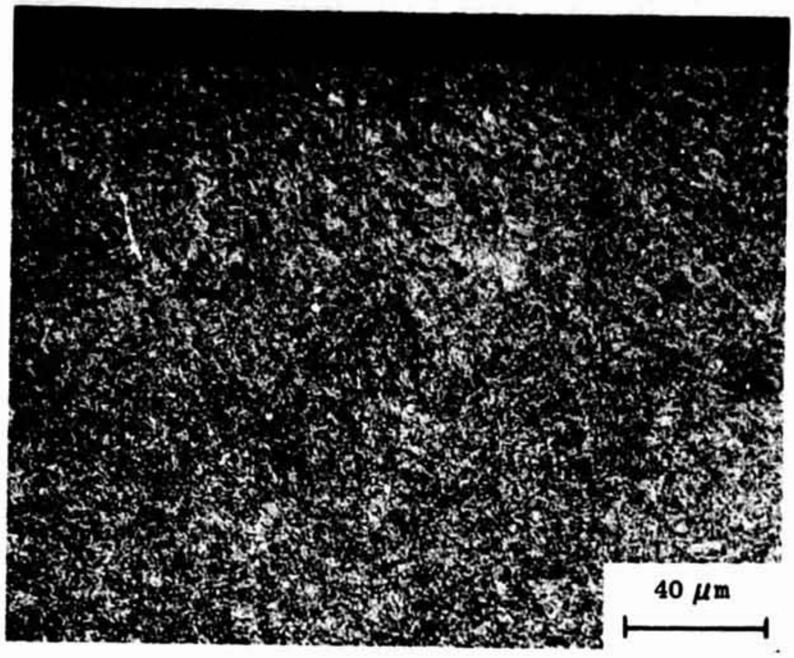
Test Conditions

S_{max} (Max. Hz Stress): 4,826 MPa (700 ksi)

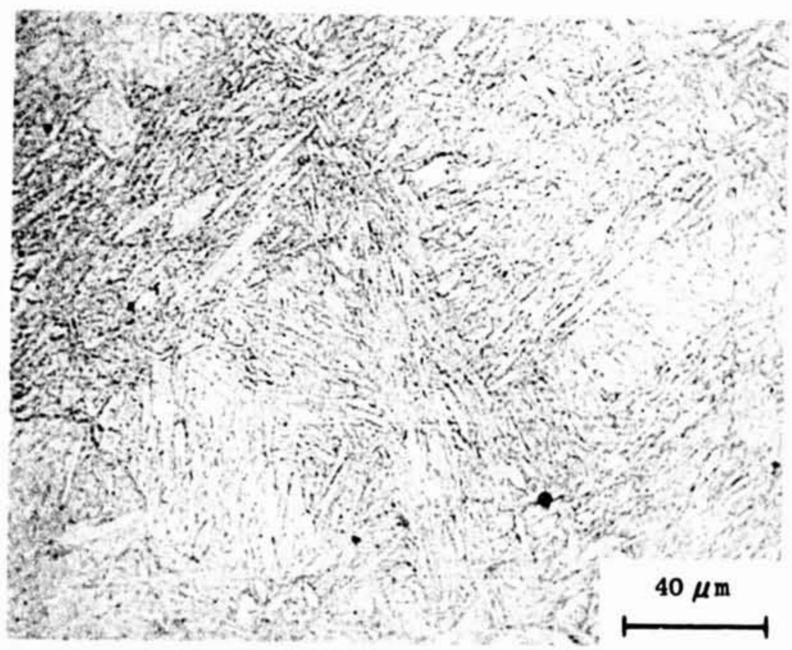
Speed: 6.23 m/sec (245 in/sec)

Lubricant: MIL-L-7808

Temperature: Room-ambient



(a)
Case



(b)
Core

Figure 20. Optical Microstructure of CBS 1000M, Test Series AI, Nital Etch.

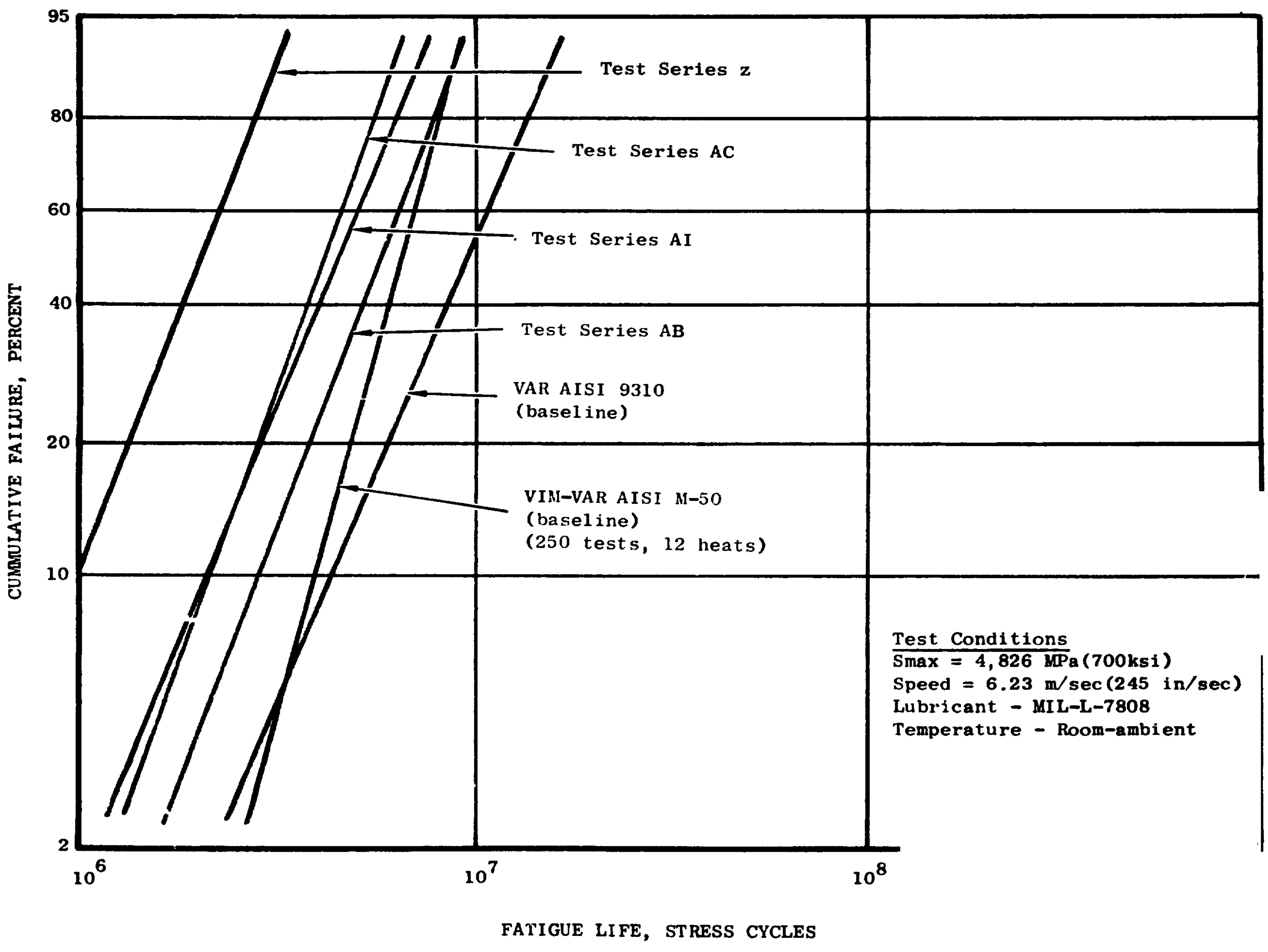


Figure 21. Fatigue Life Comparison of CBS 1000M

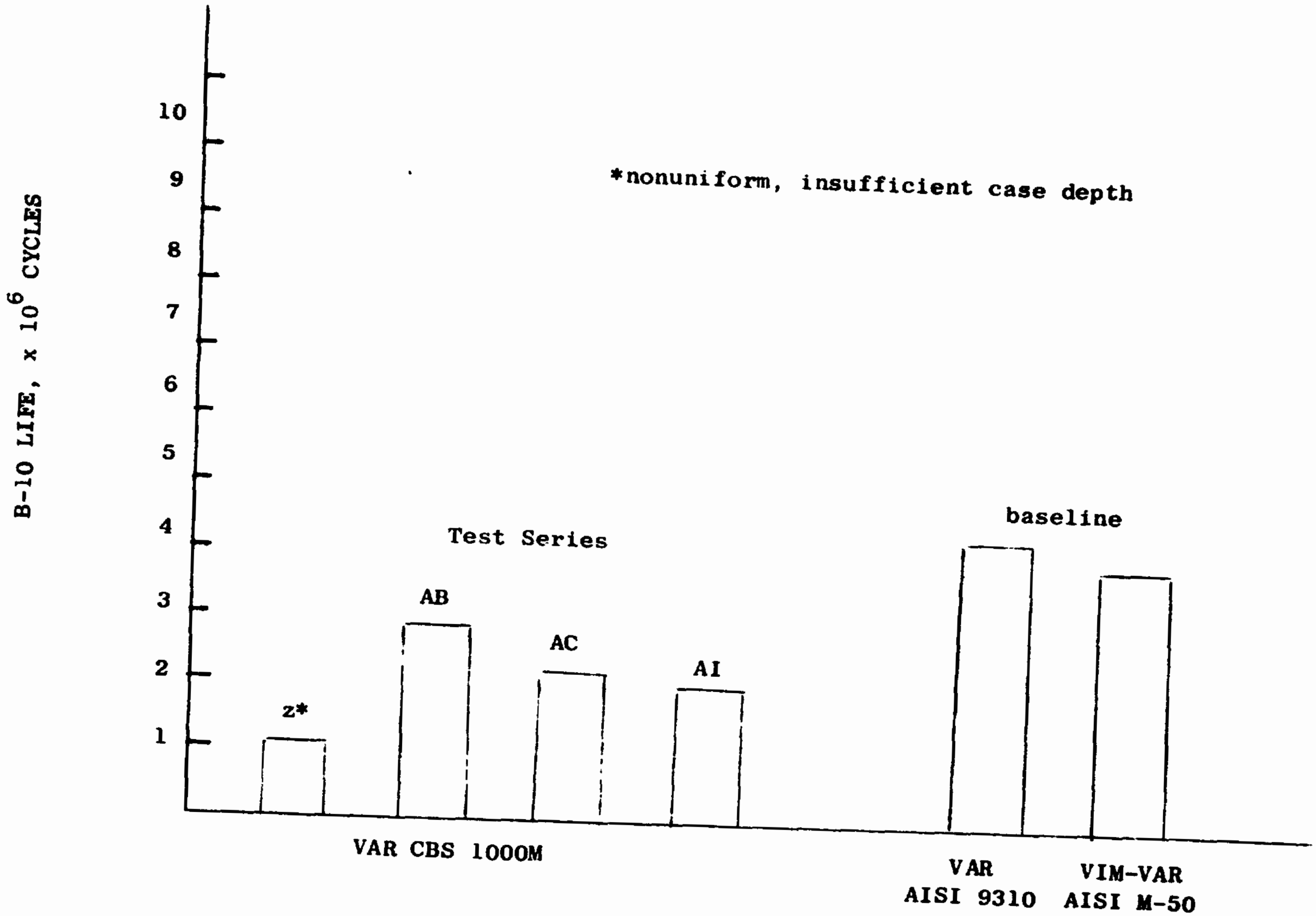


Figure 22. B-10 Fatigue Life Comparision of CBS 1000M.

that VAR CBS1000M is inferior to both VIM-VAR AISI M-50 and to VAR AISI 9310. However, the difference is statistically insignificant.

g) Vasco X-2

Metallurgically, Vasco X-2 is similar to CBS1000M. Both CBS1000M and Vasco X-2 have case microstructure similar to those of high speed tool steels. Chemical compositions of Vasco X-2 used in these investigations are given in Table 20. Table 21 summarizes heat treating processes used for all test series for Vasco X-2. Austenitizing temperature was 1010°C (1850°F) and tempering temperature was 316°C (600°F) except for test series AK where 510°C (950°F) tempering was employed. To find the effect of shot peening on RCF, test series AM was shot peened after being heat treated the same as test series AL.

Table 22 summarizes RCF test results and metallurgical characteristics of Vasco X-2. Weibull plots of RCF data for VAR Vasco X-2 are shown in Figure 23 where the data of VIM-VAR AISI M-50 and VAR AISI 9310 are included for comparison. B-10 lives are also shown as a bar chart in Figure 24. Microstructures of each test series for Vasco X-2 are presented in Figures 25 through 28.

Volume percent of retained austenite was varied from 0 to 22%, being more than for the case of CBS1000M. The reason may be attributed to the lower tempering temperatures used for Vasco X-2. It is also shown that RCF life was increased when retained austenite is increased. It is also consistent with the general observation in that retained austenite is less with specimens tempered at higher temperatures (compare test series AJ with AK).

RCF performance of Vasco X-2 is considered to be inferior or equal to VIM-VAR AISI M-50 and VAR AISI 9310. It is interesting to note that when retained austenite in the case structure of Vasco X-2 is minimal, the RCF performance becomes comparable to that of CBS1000M.

The shot peening left the bar surface with a rough, 1.27 μm (50 μin) rms finish. A final grind was used, removing about 0.025 mm (0.001 in), to get the bar surface within the finish specification. Circumferential residual stress distribution in Vasco X-2 (test series AL and AM) is given in Table 23 and plotted in Figure 29. In Figure 29, the depth of maximum shear stress (0.007 in) is indicated where compressive stress is -827 MPa (-120 ksi) for shot peened and -207 MPa (-30 ksi) for nonshot peened. Unexpectedly, it appears that shot peening is not

TABLE 20

CHEMICAL COMPOSITION OF VASCO X-2

Alloying Element, Percent by Weight (Balance Fe)

Test Series	Heat Number	C	Si	Mn	S	P	W	Cr	V	Mo	Co	Ni	Cu
S	03357	0.12	0.88	0.29	0.008	0.012	1.32	4.95	0.42	1.34	0.02	0.06	0.09
AJ & AK	2960-A	0.12	0.88	0.29	0.008	0.012	1.32	4.95	0.42	1.34	0.02	0.06	0.09
AL & AM	3903-A	0.14	0.95	0.24	0.011	0.011	1.40	4.76	0.45	1.40	0.03	0.10	0.06

TABLE 21

HEAT TREATING PROCESS FOR VASCO X-2

Heat Treating	Test Series δ	AJ	AK	AL	AM
Preheat	1010°C (1850°F) 2-3 hours in air	Heat to 843°C (1550°F) in air and equalize, heat to 1010°C (1850°F) in air, hold 30 min., air cool	Same as Test Series AJ.	--	--
Carburize	927°C/954°C (1700°F/ 1750°F)	954°C (1750°F) 7 hours in endo-thermic gas	Same as Test Series AJ.	927°C (1700°F) for 1.75 hrs, oil quench from 788°C (1450°F), snap temper at 149°C (300°F) 2 hours	
Austen-itize	1010°C (1850°F) 1 hour, oil quench	1010°C (1850°F) in protective atmos-phere 1 hour, oil quench	Same as Test Series AJ.	Preheat to 816°C (1500°F), 1010°C (1850°F), 10 min.	
Deep Freeze	--	-73°C (-100°F) 3 hours	Same as Test Series AJ.	--	--
Temper	Temper 316°C (600°F) 2+2+2 hours	Temper 316°C (600°F) 2+2+2 hours	Temper 510°C (950°F) 2+2+2 hours	Temper 316°C (600°F) 2+2 hrs.	
Shot Peen	--	--	--	--	Shot Peened

TABLE 22

SUMMARY OF RCF TEST RESULTS AND METALLURGICAL CHARACTERISTICS OF VASCO X-2

Test Series	B-10 Life, x 10^6 Cycles	B-50 Life, x 10^6 Cycles	Weibull Slope	Failure[(a)] Index	Effective Case Depth mm (in)	Core Hardness HRC	Case Hardness HRC	Retained Austenite Vol. %	Remarks
δ	6.31	15.13	2.16	20/20	0.89 (0.035)	60.0	43.0	22.0	Phase I 316°C temper
AJ	2.88	8.55	1.73	10/10	0.76 (0.030)	61.8	42.0	5.0	Phase III 316°C temper
AK	1.56	3.93	2.03	10/10	0.76 (0.030)	60.5	46.0	N.D.[(b)]	Phase III 510°C temper
AL	3.63	12.24	1.55	10/10	0.64 (0.025)	60.6	43.0	11.0	Phase III 316°C temper
AM	2.30	4.42	2.89	13/13	0.64 (0.025)	62.4	43.0	11.0	Phase III 316°C temper, shot peened

(a) - Number of failures out of total number of tests.
(b) - Not detected.

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
Lubricant: MIL-L-7808
Temperature: Room-ambient

TABLE 23

CIRCUMFERENTIAL RESIDUAL STRESS

DISTRIBUTIONS IN AS-RECEIVED VASCO X-2 SPECIMENS

(By X-ray Technique)

Depth Below Surface ($x10^{-3}$ in)	Residual Stress	
	Test Series AL MPa (ksi)	Test Series AM** MPa (ksi)
0 (0)	-827 (-120)*	-827 (-120)*
25 (1)	-434 (-63)	-827 (-120)*
51 (2)	0 (0)	-827 (-120)*
76. (3)	-179 (-26)	-827 (-120)*
127 (5)	-179 (-26)	-827 (-120)*
254 (10)	-434 (-63)	-827 (-120)*
381 (15)	-827 (-120)*	-434 (-63)
406 (16)		-517 (-75)
457 (18)		-434 (-63)
508 (20)		-345 (-50)

*Greater than -827 MPa (-120 ksi)

**(0.001") 0.254 μm was removed from the surface by final grinding before testing.

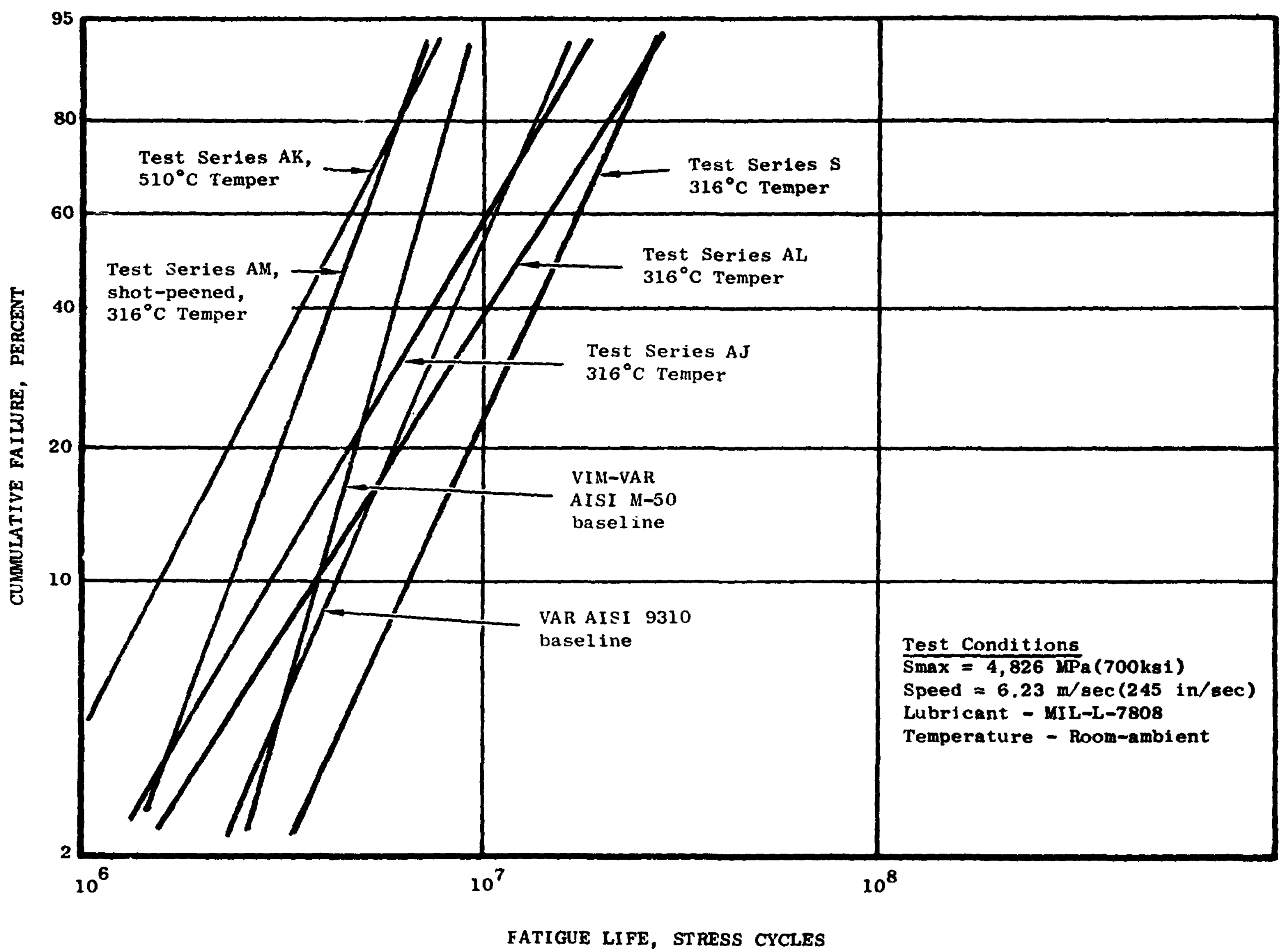


Figure 23. Fatigue Life Comparison of Vasco X-2.

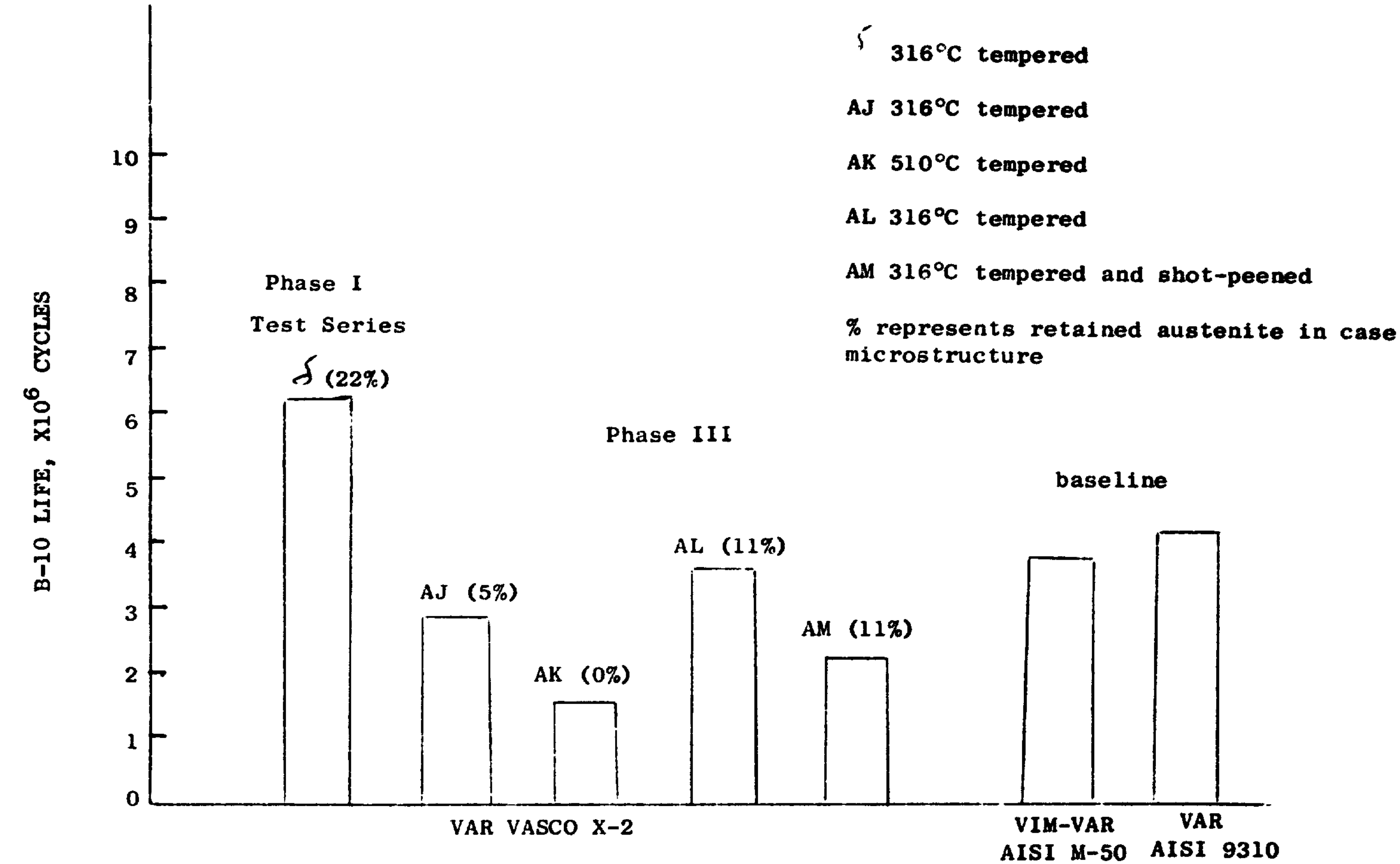
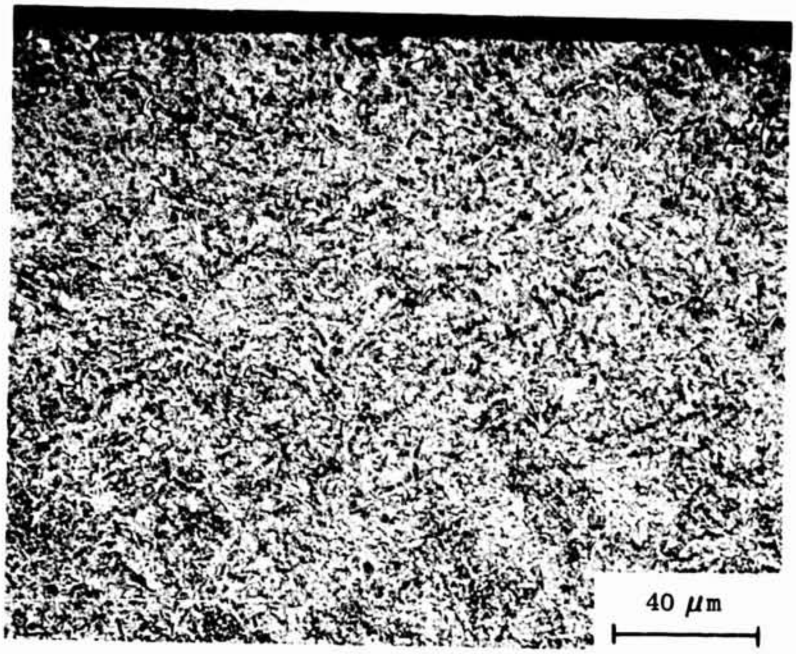
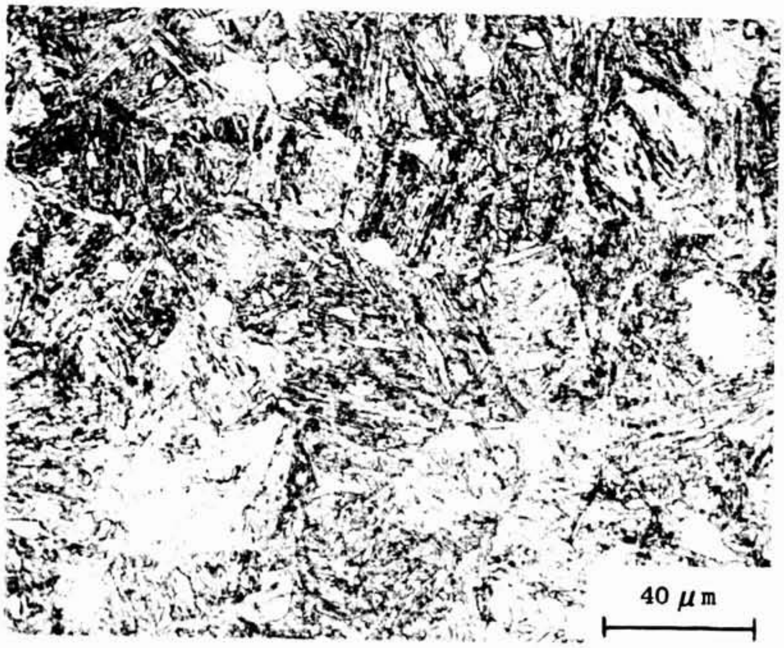


Figure 24. B-10 Fatigue Life Comparision of VAR Vasco X-2.

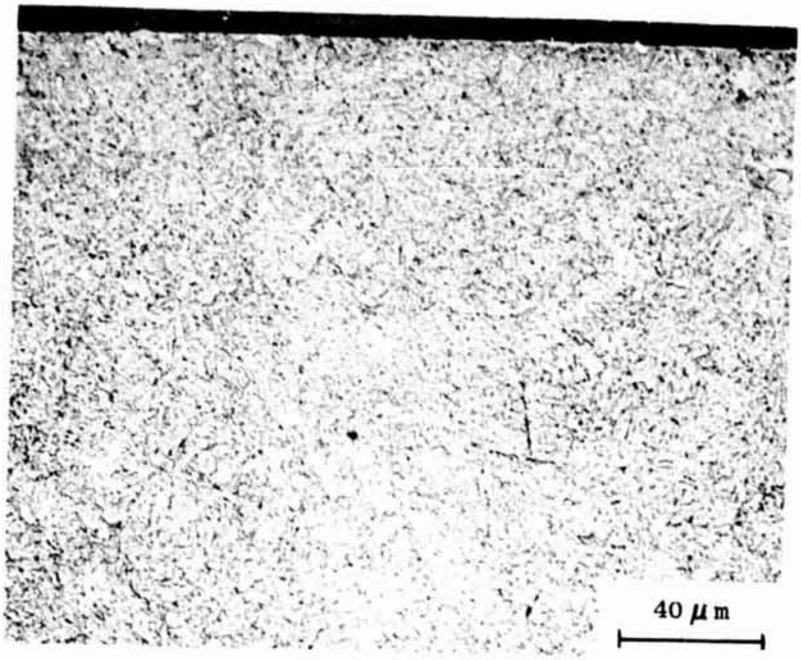


(a)
Case

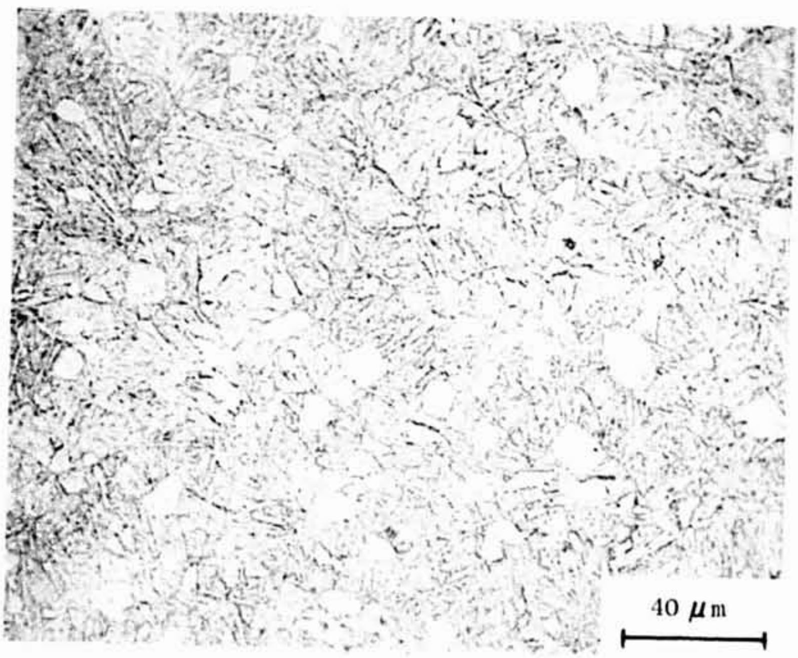


(b)
Core

Figure 25. Microstructure of Vasco X-2, Test Series AJ, Picral Etch.

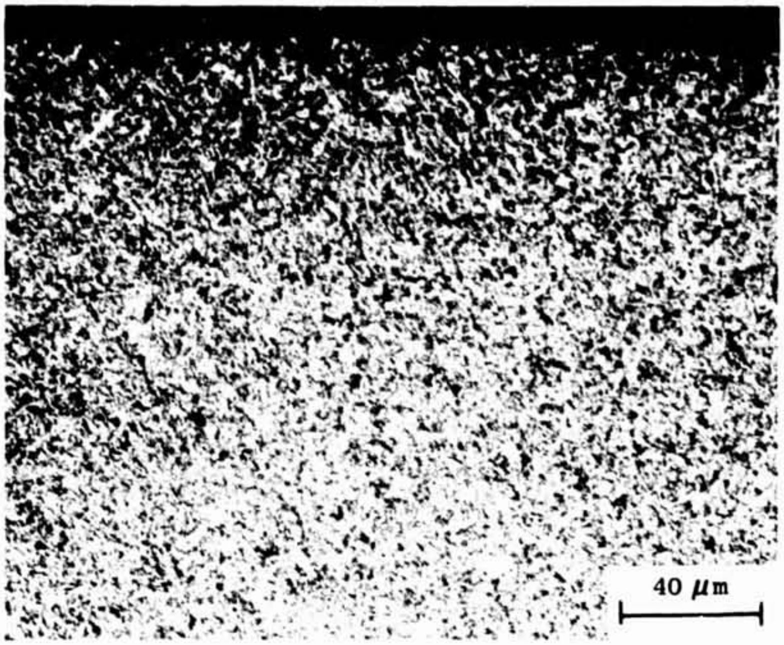


(a)
Case

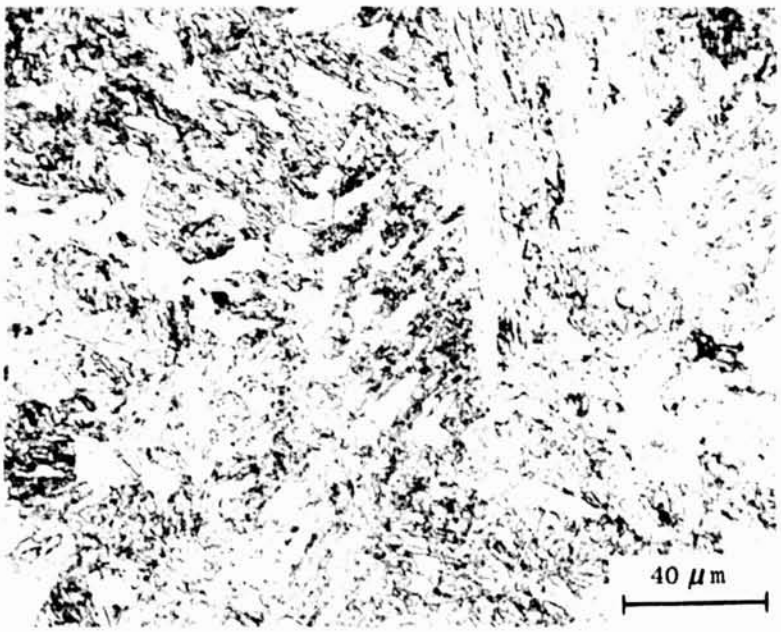


(b)
Core

Figure 26. Microstructure of Vasco X-s, Test Series AK, Nital Etch.

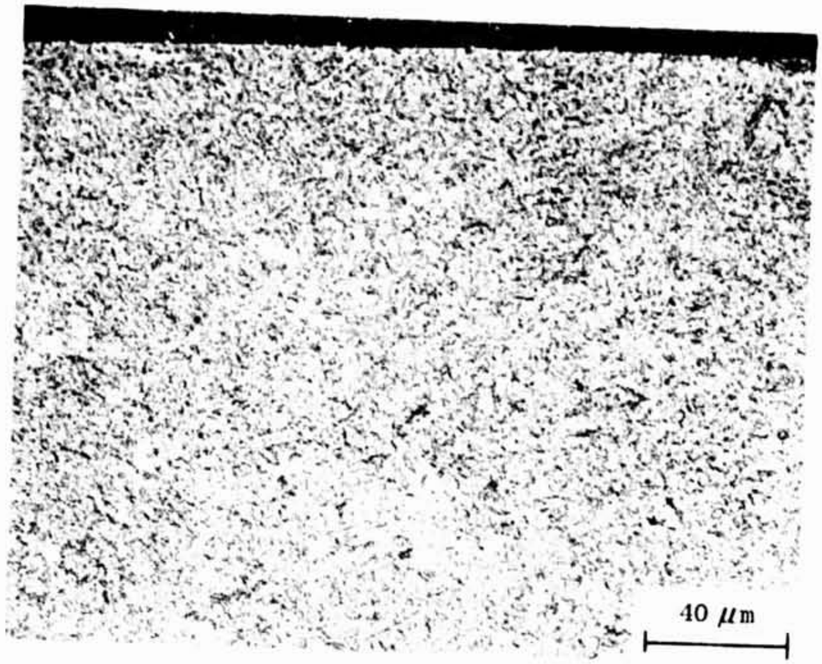


(a)
Case

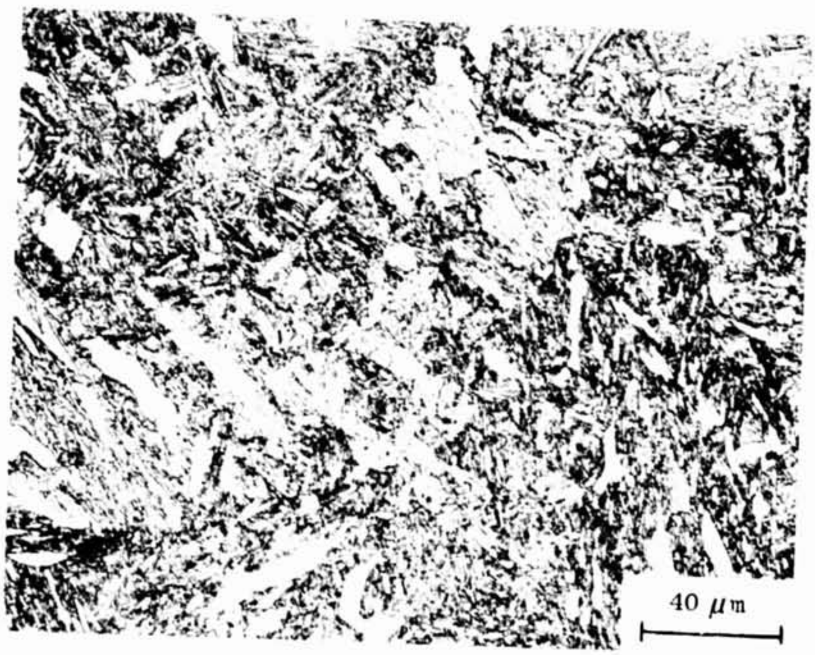


(b)
Core

Figure 27. Microstructure of Vasco X-s, Test Series AL, Picral Etch.



(a)
Case



(b)
Core

Figure 28. Microstructure of Vasco X-2,
Test Series AM, Picral Etch.

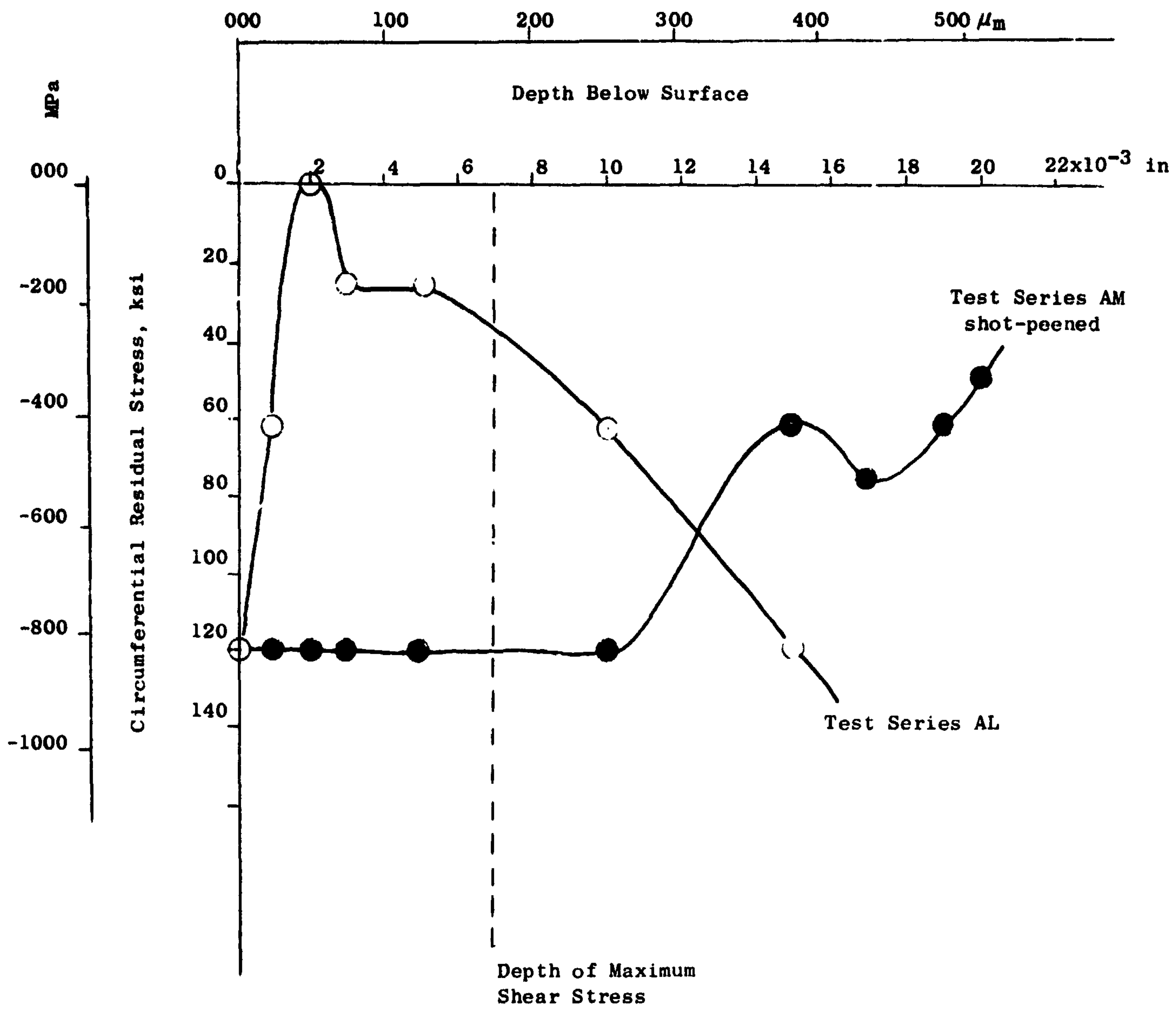


Figure 29. Circumferential Residual Stress as a Function of Depth Below Surface of Vascc X-2 Specimens.

beneficial to RCF performance. The reason for this is not known at the present time.

All previous investigations with the exception of Kepple and Mattson's study[12] show that compressive stresses introduced either mechanically or metallurgically processed (i.e., case hardening) are beneficial to rolling contact fatigue lives. For a detailed literature review, read Reference (13). However, Kepple and Mattson reported that compressive stresses induced by interference fits did not show any improvement on rolling element fatigue life. It is interesting to note that all studies showed the detrimental effect of tensile stresses to rolling contact fatigue life performance.

h) <u>VascoMax 350 and Vasco Matrix II</u>

Chemical compositions of VAR VascoMax 350 (test series AN) and VAR Vasco Matrix II (test series AT and AO) are described in Table 24. Table 25 summarizes the heat treating procedures used in this investigation. VAR VascoMax 350 (test series AN) was aged at 488°-504°C (910°-940°F) to have HRC 59.5 through precipitation hardening in martensite matrix structure. VAR Vasco Matrix II was through-hardened in a similar manner to other high strength tool steels such as AISI M-50.

Table 26 summarizes RCF tests and metallurgical analyses on these alloys. Microstructures are shown in Figures 30 and 31. Volume percent retained austenite was measured to be low by X-ray diffraction technique. Weibull plots of tested materials are given in Figure 22.

Based on the present results, it is concluded that VAR VascoMax 350 is inferior to VIM-VAR AISI M-50 or VAR AISI 9310. This may be due to the partly low hardness inherent in this material, but the magnitude of high difference is probably greater than could be expected for hardness alone. It is also shown that VAR Vasco Matrix II is equivalent to VIM-VAR AISI M-50 and VAR AISI 9310 in RCF life strength.

TABLE 24

CHEMICAL COMPOSITION OF VASCOMAX 350 AND VASCO MATRIX II

Phase	Test Series	Test Materials	Alloying Elements, Weight Percent (Balance Fe)												
			C	Si	Mn	S	P	W	Cr	V	Mo	Co	Ni	Al	Cu
III	AN	VascoMax 350 (VAR)	0.15	0.03	0.02	0.006	0.004	1.37	--	--	4.76	11.75	18.61	0.11	--
I	W	Vasco Matrix II (VAR)	0.57	0.22	0.026	0.021	0.008	1.02	3.86	1.0	5.07	7.82	--	--	--
III	AO	Vasco Matrix II (VAR)	0.53	0.21	0.12	0.013	0.014	1.10	4.13	1.08	4.80	7.81	0.10	--	0.12

TABLE 25

HEAT TREATING PROCESS FOR VASCOMAX 350 AND VASCO MATRIX II

Heat Treating	Phase III VAR VascoMax 350 (Test Series AN)	Phase I VAR Vasco Matrix II (Test Series W)	Phase III VAR Vasco Matrix II (Test Series AO)
Preheat	--	899°C (1650°F) 30 minutes, air cool to RT	--
Austenitize	--	1104°C (2020°F) quench in salt at 538°C (1000°F), air cool to RT	1116°C (2040°F) for 15 minutes, quench in salt bath at 607°C (1125°F), air cool to RT
Temper	Age harden to HRC 59-60 for 3 hours at 488-504°C (910-940°F), air cool to RT	510°C (950°F) 2+2 hours	538°C (1000°F) 2+1 hours

TABLE 26

SUMMARY OF RCF TEST RESULTS AND METALLURGICAL CHARACTERISTICS OF VASCOMAX 350 AND VASCO MATRIX II

Phase	Test Series	Test Materials	B-10 Life, $\times 10^6$ Cycles	B-50 Life, $\times 10^6$ Cycles	Weibull Slope	Failure[a] Index	Hardness HRC	Retained Austenite Vol. %
III	AN	VascoMax 350 (VAR)	0.14	0.77	1.09	10/10	59.5	N.D.[b]
I	[illegible]	Vasco Matrix II (VAR)	3.60	8.03	2.35	20/20	62.6	1.2
III	AO	Vasco Matrix II (VAR)	3.31	13.89	1.31	10/10	61.8	N.D.

(a) - Number of failures out of total number of tests.

(b) - Not detected.

Test Conditions

S_{max} = 4,826 MPa (700 ksi)

Speed = 6.23 m/sec (245 in/sec)

Lubricant: MIL-L-7808

Temperature: Room-ambient

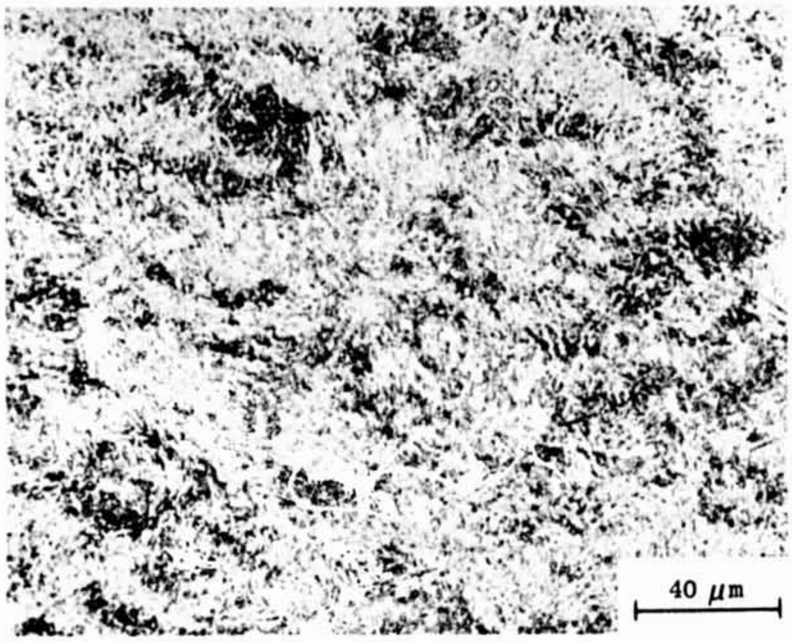


Figure [illegible]0. Optical Microstructure of VascoMax 350,
Test Series AN, Nital Etch.

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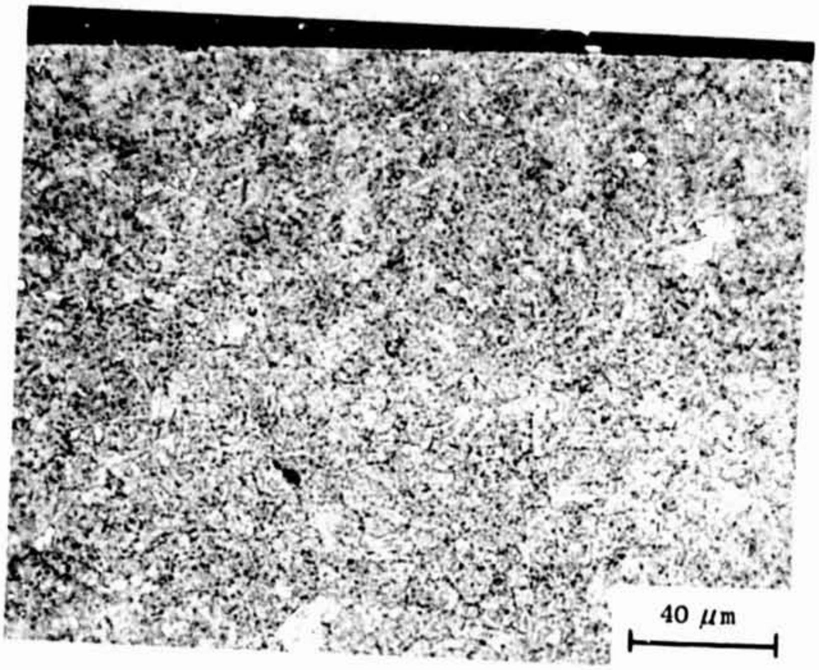

Figure 31. Optical Microstructure of Vasco Matrix II
Test Series AO, Nital Etch.

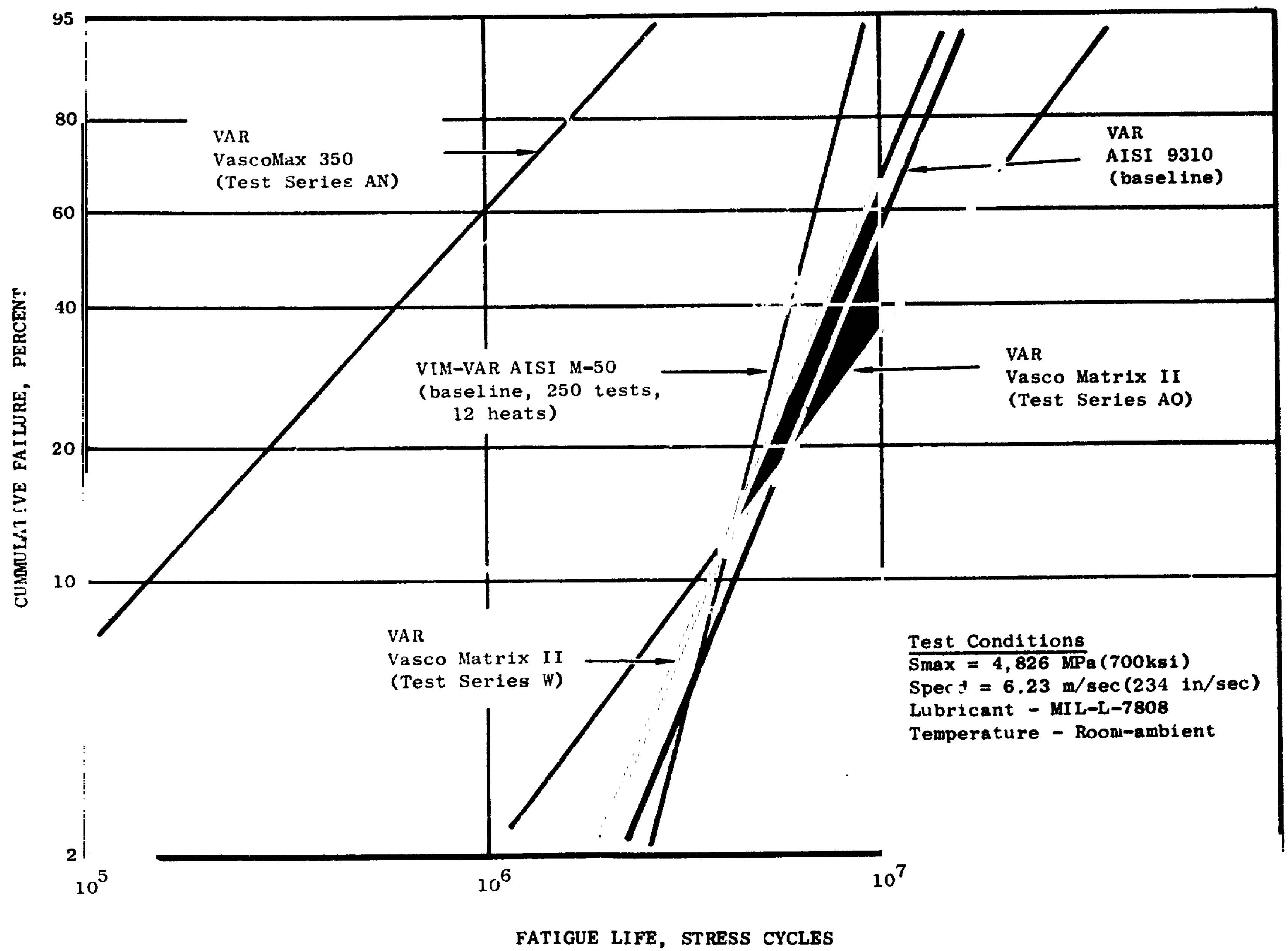

Figure 32. Fatigue Life Comparison of VascoMax 350 and Vaco Matrix II.

IV. SUMMARY AND CONCLUSIONS

Rolling element fatigue lives of nine alloys were evaluated in the General Electric Rolling Contact (RC) rigs. Test conditions used in the GE RC rigs with cylindrical specimens included a Hertzian stress at 4,826 MPa (700 ksi), a rolling speed of 6.23 m/sec (245 in/sec.). Tests were run with a Type I oil (MIL-L-7808G) at room temperature. Metallurgical analyses were made before and after the RC rig tests. Test data were statistically analyzed using the Weibull distribution function. B-10 lives (10% failure rate) of alloys were compared versus reference alloys, VIM-VAR AISI M-50 and VAR AISI 9310.

The alloys studied were six case carburizing alloys (AISI 9310, CBS600, CBS1000M, EX00014, Vasco X-2 and EX00053) and three through-hardening alloys (AISI M-50, VascoMax 350 and Vasco Mat .x II). The effects of different heat treatments, vacuum melting processes, shot peening, gold plating and chrome plating on RCF performance were studied with selected alloys.

- All alloys except VascoMax 350 investigated in this final phase of the study (Phase III) showed RCF performance inferior or equivalent to that of AISI 9310 and of AISI M-50. However, the differences were not statistically significant. VascoMax 350 showed very poor RCF life.

- Double vacuum processing (VIM-VAR) was found to improve RCF performance over that of single vacuum processing (VAR) in both AISI M-50 a id AISI 9310, but in this study the improvements were not statistically significant.

- The effects of different tempering temperatures employed and the introduction of freezing cycles did not significantly affect RCF life of Vasco X-2.

- Shot peening the surface of Vasco X-2 test bars failed to show the improvement in RCF life expected due to beneficial subsurface compressive residual stress.

- Neither gold nor chrome plating were beneficial to RCF performance of VIM-VAR AISI M-50. Chrome plating gave lives less than the baseline VIM-VAR M-50, but the difference was not statistically significant.

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12. R. J. Parker and E. V. Zaretsky, "Effect of Residual Stresses Induced by Prestressing on Rolling Element Fatigue Life", NASA TN D-6995, October 1972.

13. R. K. Kepple and R. L. Mattson, "Rolling Element Fatigue and Macroresidual Stress", J. Lub. Tech., ASME Trans., Vol. 92, No. 1, January 1970, pp 76-82.

APPENDIX A

TABLE 27

CHEMICAL COMPOSITION OF TEST MATERIALS FOR PHASE III

Test Series	Material (Melting Process)	Alloying Element, Percent by Weight (Balance Fe)													Remarks
		C	Si	Mn	S	P	W	Cr	V	Mo	Co	Ni	Al	Cu	
AG	AISI M-50 (VIM-VAR)	0.82	0.24	0.26	0.003	0.010	0.02	4.16	1.06	4.32	0.03	0.08		0.08	
AH	CBS600 (AM)	0.19	1.05	0.61	0.014	0.007	--	1.50	--	0.94	--	0.18	--	--	
AI	CBS1000M (VAR)	0.14	0.43	0.48	0.019	0.018	--	1.12	--	4.77	--	2.94	--	--	
AJ	Vasco X-2 (VAR)	0.12	0.88	0.29	0.008	0.012	1.32	4.95	0.42	1.34	0.02	0.06	--	0.09	316°C (600°F) temper
AK	Vasco X-2 (VAR)	Same as Test Series AJ													510°C (950°F) temper
AL	Vasco X-2 (VAR)	0.14	0.94	0.24	0.011	0.011	1.40	4.76	0.45	1.40	0.03	0.10	--	0.06	316°C (600°F) temper
AM	Vasco X-2 (VAR)	Same as Test Series AI													316°C (600°F) temper + shot peened
AN	Vasco-Max 350 (VAR)	0.15	0.03	0.02	0.006	0.004	1.37	--	--	4.76	11.75	18.61	0.11	--	

TABLE 27 (Continued) **Page 2.**

CHEMICAL COMPOSITION OF TEST MATERIALS FOR PHASE III

Test Series	Material (Melting Process)	Alloying Element, Percent by Weight (Balance Fe)													Remarks
		C	Si	Mn	S	P	W	Cr	V	Mo	Co	Ni	Al	Cu	
AO	Vasco Matrix II (VAR)	0.53	0.21	0.12	0.013	0.014	1.10	4.13	1.08	4.80	7.81	0.10	--	0.12	
AP	AISI M-50 (VAR)	0.80	0.22	0.24	0.005	0.006	0.04	3.98	0.98	4.18	0.05	0.07	--	0.06	
AO	AISI 9310 (VAR)	0.10	0.28	0.54	0.001	0.006	--	1.18	--	0.11	--	3.15	--	0.06	
AR	AISI 9310 (VIM-VAR)	0.11	0.32	0.54	0.004	0.005	--	1.26	--	0.12	--	3.16	--	0.06	
AS	EX00014 (VAR)	0.11	0.99	0.36	0.004	0.008	--	0.99	0.11	0.75	--	2.96	--	2.04	
AT	EX00053 (VAR)	0.10	0.98	0.37	0.006	0.009	--	1.05	0.12	3.30	--	2.13	--	2.07	
AU	AISI M-50 (VIM-VAR)	Same as Test Series AG													Gold Plated
AV	AISI M-50 (VIM-VAR)	Same as Test Series AG													Chrome Plated

APPENDIX B

TABLE 28

PHYSICAL PROPERTIES OF LUBRICANT, STAUFFER JET I

(MIL-L-7808G)

Kinematic Viscosity, cs		Source
-20°F	480.	(2)
100	14.76	(1)
210	3.70	(1)
400	1.2	(2)
Fire Point, °F	490	(3)
Flash Point, °F	425	(1)
Specific Gravity, 60/60°F	0.950	(3)
Vapor Pressure, mm Hg		
100°F	ca. 10^{-5}	(4)
350°F	0.88	(4)
400°F	1.45	(4)
Specific Heat, BTU/lb-°F		
100°F	.470	(2)

(1) - Batch 3979

(2) - Vendor Data, Extrapolated or Interpolated

(3) - Vendor Brochure

(4) - AF Data

APPENDIX C

TABLE 29

ROLLING CONTACT FATIGUE TESTS - VIM-VAR AISI M-50

(Test Series AG)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number			Stress Cycles to Failure	
1	15		8,160,000	9,810,000
2	16		2,100,000	13,950,000
3	17		4,110,000	15,630,000
4	18		8,550,000	7,050,000
5	19		3,165,000	11,164,000
6	20		4,695,000	4,550,000
7	21		13,455,000	3,960,000
8	22		9,900,000	10,150,000
9	23		6,825,000	8,165,000
10	24		3,615,000	20,770,000
11	25		14,100,000	5,400,000
12	26		5,625,000	5,250,000
13	27		12,285,000	13,770,000
14			7,725,000	

Weibull Analysis

B-10 Life: 3.34×10^6 cycles
B-50 Life: 7.77×10^6 cycles
Slope: 2.23

TABLE 30

ROLLING CONTACT FATIGUE TESTS - AM CBS600

(Test Series AH)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed - 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		27,420,000
2		3,000,000
3		4,545,000
4		4,695,000
5		2,190,000
6		4,890,000
7		7,890,000
8		11,505,000
9		13,830,000
10		5,985,000

Weibull Analysis

B-10 Life: 1.91×10^6 cycles
B-50 Life: 7.31×10^6 cycles
Slope: 1.40

TABLE 31

ROLLING CONTACT FATIGUE TESTS - VAR CBS1000M

(Test Series AI)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		6,885,000
2		5,670,000
3		2,445,000
4		3,510,000
5		1,770,000
6		5,775,000
7		5,970,000
8		4,125,000
9		3,345,000
10		4,710,000

Weibull Analysis

B-10 Life: 2.08×10^6 cycles
B-50 Life: 4.36×10^6 cycles
Slope: 2.55

TABLE 32

ROLLING CONTACT FATIGUE TESTS - VAR VASCO X-2 (316°C TEMPER)

(Test Series AJ)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		2,455,000
2		16,350,000
3		6,965,000
4		5,310,000
5		7,200,000
6		7,485,000
7		3,870,000
8		12,650,000
9		11,805,000
10		18,240,000

Weibull Analysis

B-10 Life: 2.88×10^6 cycles
B-50 Life: 8.55×10^6 cycles
Slope: 1.73

TABLE 33

ROLLING CONTACT FATIGUE TESTS - VAR VASCO X-2 (510°C TEMPER)

(Test Series AK)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		4,125,000
2		2,700,000
3		2,010,000
4		4,290,000
5		6,300,000
6		3,030,000
7		2,880,000
8		6,950,000
9		1,500,000
10		7,410,000

Weibull Analysis

B-10 Life: 1.56 x 10^6 cycles
B-50 Life: 3.93 x 10^6 cycles
Slope: 2.03

TABLE 34

ROLLING CONTACT FATIGUE TESTS - VAR VASCO X-2 (316°C TEMPER)

(Test Series AL)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		17,340,000
2		16,950,000
3		9,750,000
4		7,135,000
5		15,150,000
6		3,225,000
7		21,180,000
8		18,450,000
9		18,165,000
10		3,855,000

Weibull Analysis

B-10 Life: 3.63×10^6 cycles
B-50 Life: 12.24×10^6 cycles
Slope: 1.55

TABLE 35

ROLLING CONTACT FATIGUE TESTS - VAR VASCO X-2 (316°C TEMPER + SHOT PEENED)

(Test Series AM)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		3,975,000
2		6,450,000
3		2,655,000
4		5,505,000
5		4,950,000
6		8,085,000
7		2,235,000
8		3,630,000
9		2,775,000
10		4,455,000
11		2,850,000
12		5,625,000
13		4,740,000

Weibull Analysis

B-10 Life: 2.30 x 10^6 cycles
B-50 Life: 4.42 x 10^6 cycles
Slope: 2.89

C-2

TABLE 36

ROLLING CONTACT FATIGUE TESTS - VAR VASCOMAX 350

(Test Series AN)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		165,000
2		210,000
3		2,070,000
4		585,000
5		225,000
6		1,890,000
7		660,000
8		600,000
9		2,415,000
10		1,050,000

Weibull Analysis
B-10 Life: 0.14×10^6 cycles
B-50 Life: 0.77×10^6 cycles
Slope: 1.09

TABLE 37

ROLLING CONTACT FATIGUE TESTS - VAR VASCO MATRIX II

(Test Series AO)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		3,060,000
2		22,000,000
3		22,860,000
4		4,180,000
5		27,000,000
6		22,005,000
7		6,465,000
8		18,450,000
9		21,810,000
10		8,160,000

Weibull Analysis
B-10 Life: 3.31 x 10^6 cycles
B-50 Life: 13.89 x 10^6 cycles
Slope: 1.31

TABLE 38

ROLLING CONTACT FATIGUE TESTS - VAR AISI M-50

(Test Series AP)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant : MIL-L-7808
Temperature: Room-ambient

Test Number			Stress Cycles to Failure	
1	11		4,680,000	3,180,000
2	12		3,285,000	5,160,000
3	13		5,610,000	2,850,000
4	14		5,130,000	4,635,000
5	15		5,520,000	4,410,000
6	16		2,805,000	3,000,000
7	17		3,855,000	6,600,000
8	18		3,870,000	2,205,000
9	19		3,375,000	2,715,000
10	20		3,885,000	3,060,000

Weibull Analysis

B-10 Life: 2.46×10^6 cycles
B-50 Life: 4.01×10^6 cycles
Slope: 3.85

TABLE 39

ROLLING CONTACT FATIGUE TESTS - VAR AISI 9310

(Test Series AQ)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		4,365,000
2		34,875,000
3		7,500,000
4		14,880,000
5		5,700,000
6		4,800,000
7		13,155,000
8		5,400,000
9		4,680,000
10		36,225,000 suspended

Weibull Analysis

B-10 Life: 2.25 x 10^6 cycles
B-50 Life: 10.63 x 10^6 cycles
Slope: 1.21

TABLE 40

ROLLING CONTACT FATIGUE TESTS - VIM-VAR AISI 9310

(Test Series AR)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		21,150,000
2		14,850,000
3		21,450,000
4		21,600,000
5		9,900,000
6		21,150,000
7		14,100,000
8		6,300,000
9		7,800,000
10		21,900,000

Weibull Analysis

B-10 Life: 6.84×10^6 cycles
B-50 Life: 15.74×10^6 cycles
Slope: 2.26

TABLE 41

ROLLING CONTACT FATIGUE TESTS - VAR EX00014

(Test Series AS)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		15,600,000
2		11,850,000
3		49,800,000
4		35,559,000
5		9,300,000
6		5,400,000
7		8,100,000
8		19,800,000
9		4,950,000
10		6,000,000

Weibull Analysis
B-10 Life: 3.27×10^6 cycles
B-50 Life: 13.85×10^6 cycles
Slope: 1.31

TABLE 42

ROLLING CONTACT FATIGUE TESTS - VAR EX00053

(Test Series AT)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		3,390,000
2		6,900,000
3		10,065,000
4		5,700,000
5		41,775,000
6		4,350,000
7		6,000,000
8		35,115,000
9		6,000,000
10		32,070,000

Weibull Analysis
B-10 Life: 1.95×10^6 cycles
B-50 Life: 11.58×10^6 cycles
Slope: 1.05

TABLE 43

ROLLING CONTACT FATIGUE TESTS - VIM-VAR AISI M-50 (Gold Plated)

(Test Series AU)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		6,585,000
2		8,385,000
3		14,790,000
4		11,550,000
5		11,025,000
6		5,040,000
7		8,760,000
8		8,710,000
9		11,565,000
10		3,450,000

Weibull Analysis

B-10 Life: 4.21×10^6 cycles
B-50 Life: 8.88×10^6 cycles
Slope: 2.53

TABLE 44

ROLLING CONTACT FATIGUE TESTS - VIM-VAR AISI M-50 (Chrome Plated)

(Test Series AV)

Test Conditions

S_{max} = 4,826 MPa (700 ksi)
Speed = 6.23 m/sec (245 in/sec)
(25,000 cycles/min.)
Lubricant: MIL-L-7808
Temperature: Room-ambient

Test Number		Stress Cycles to Failure
1		3,795,000
2		19,515,000
3		22,890,000
4		11,910,000
5		14,535,000
6		2,700,000
7		9,750,000
8		24,660,000
9		12,225,000
10		2,250,000

Weibull Analysis

B-10 Life: 2.28 x 10^6 cycles
B-50 Life: 10.66 x 10^6 cycles
Slope: 1.22

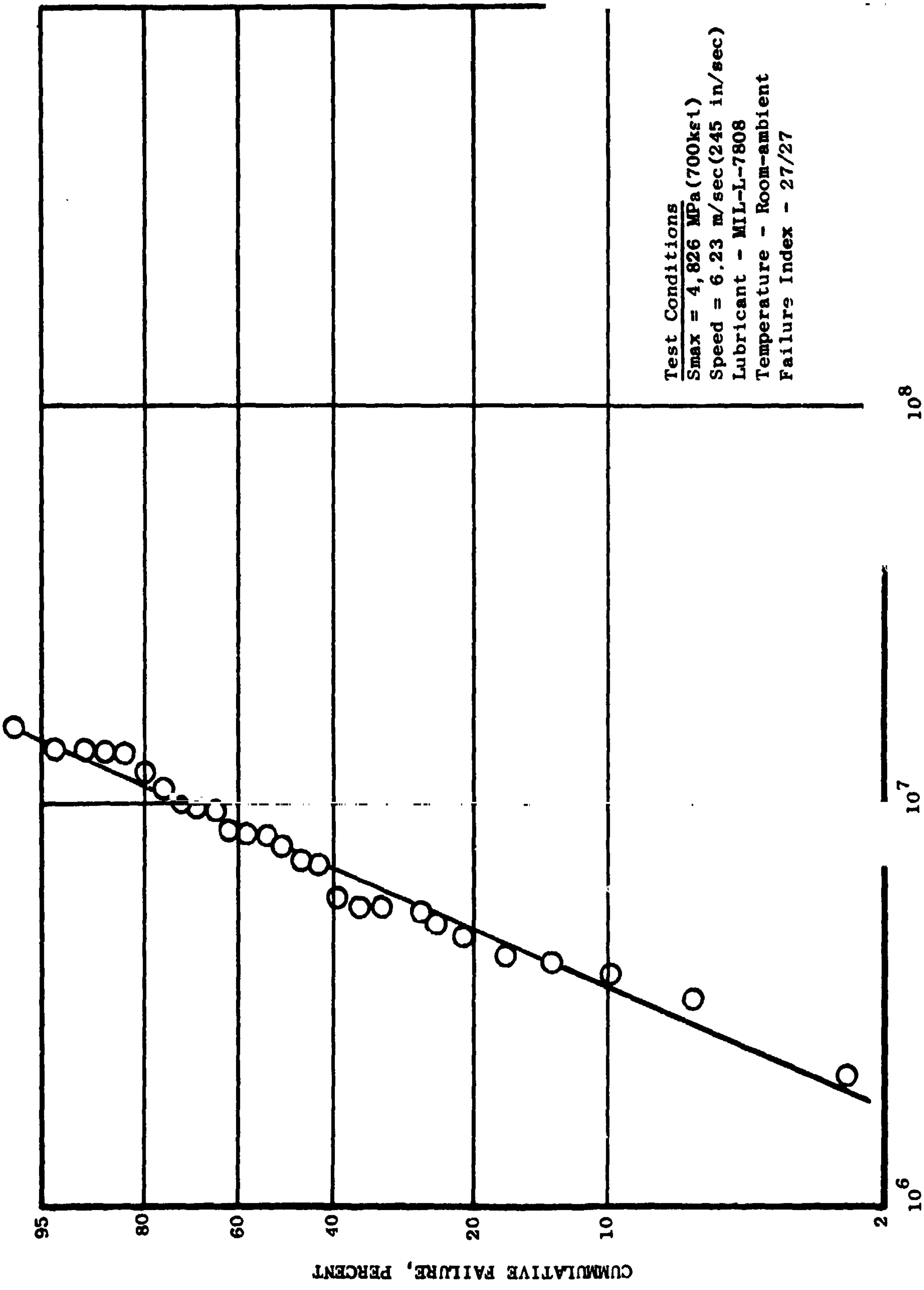

Figure 33. RCF Test Results of VIM-VAR AISI M-50 (Test Series AG)

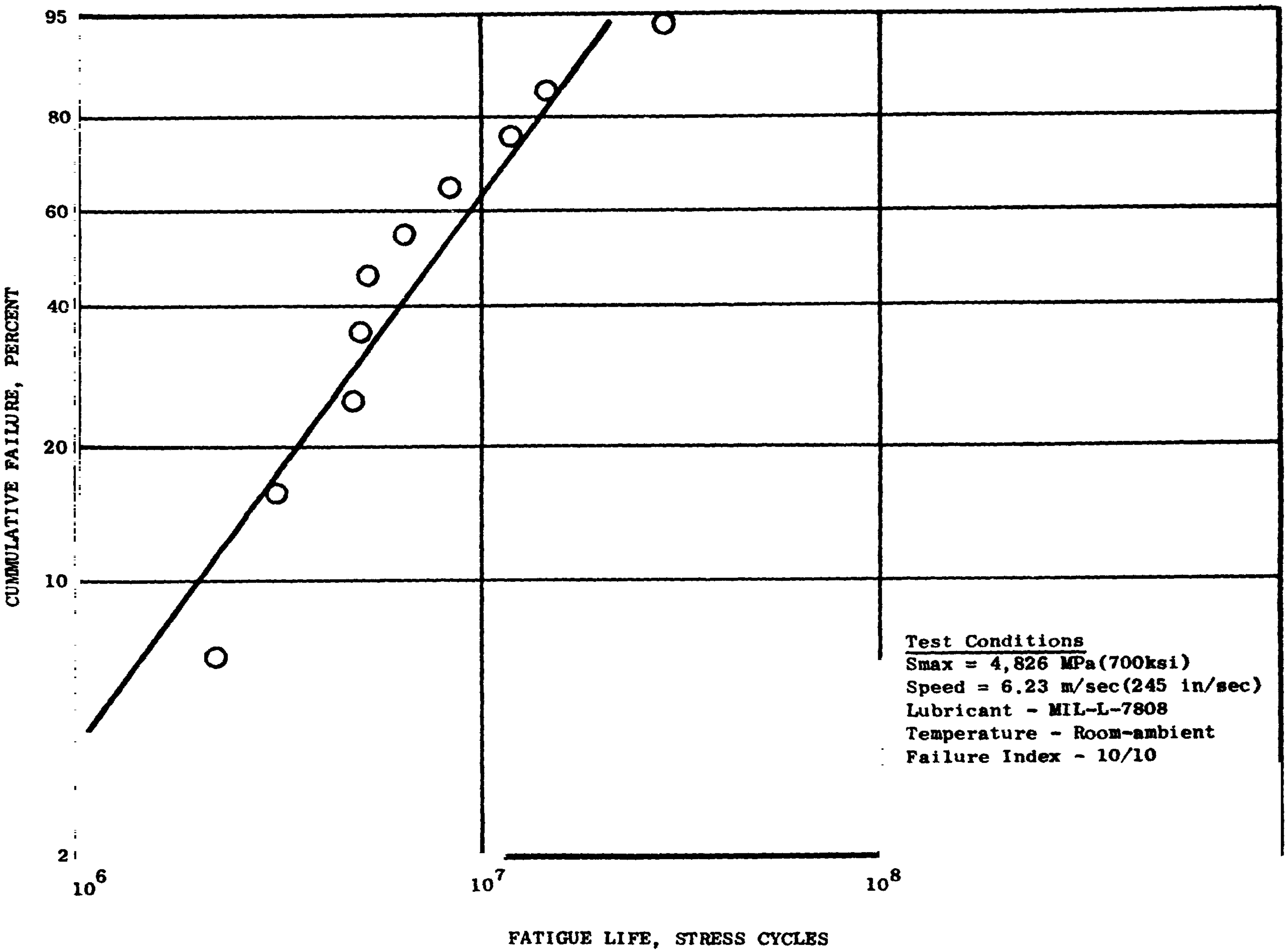

Figure 34. RCE Test Results of AM CBS 600 (Test Series AH)

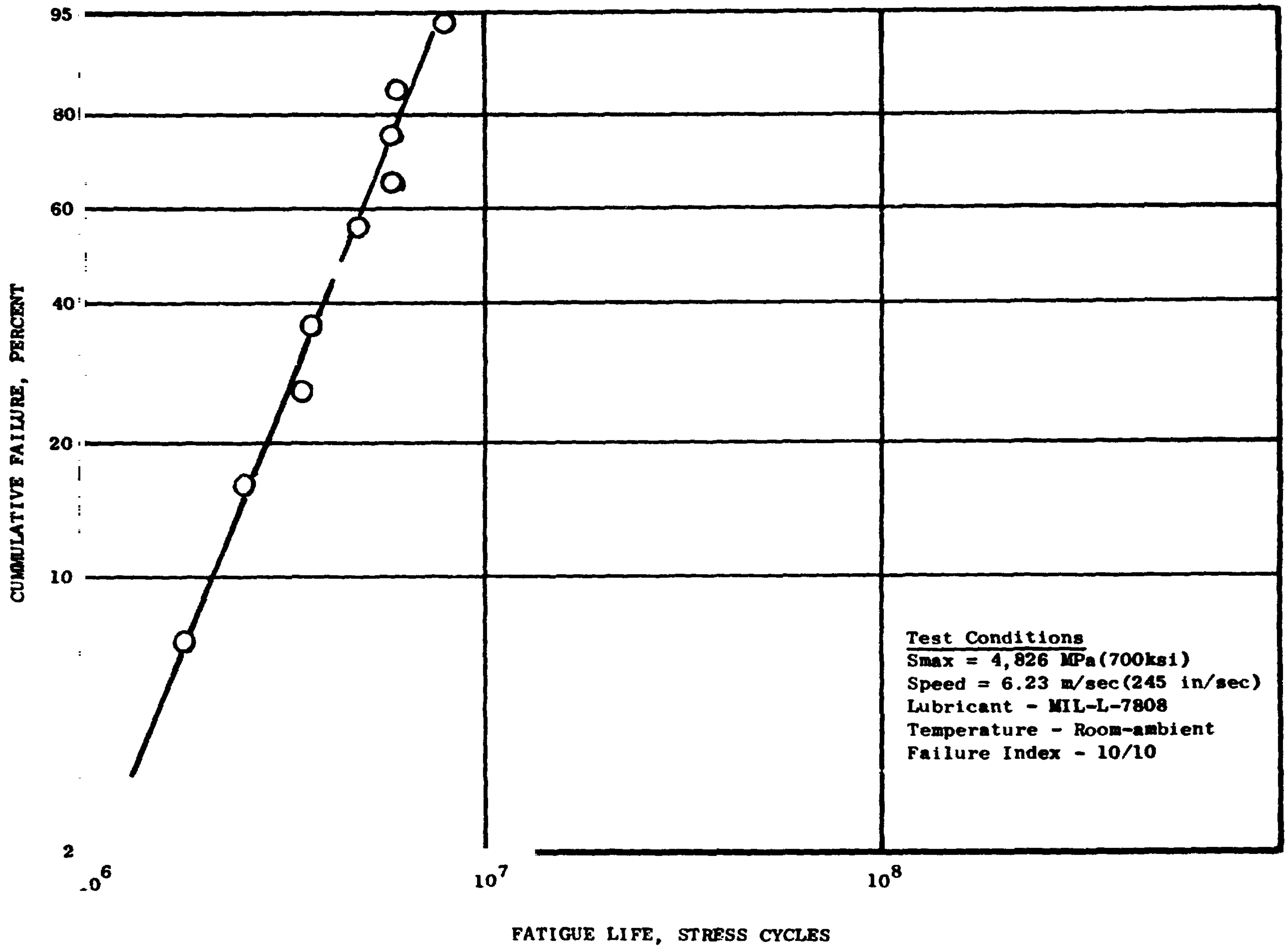

Figure 35. RCF Test Results of VAR CBS-1000M (Test Series AI)

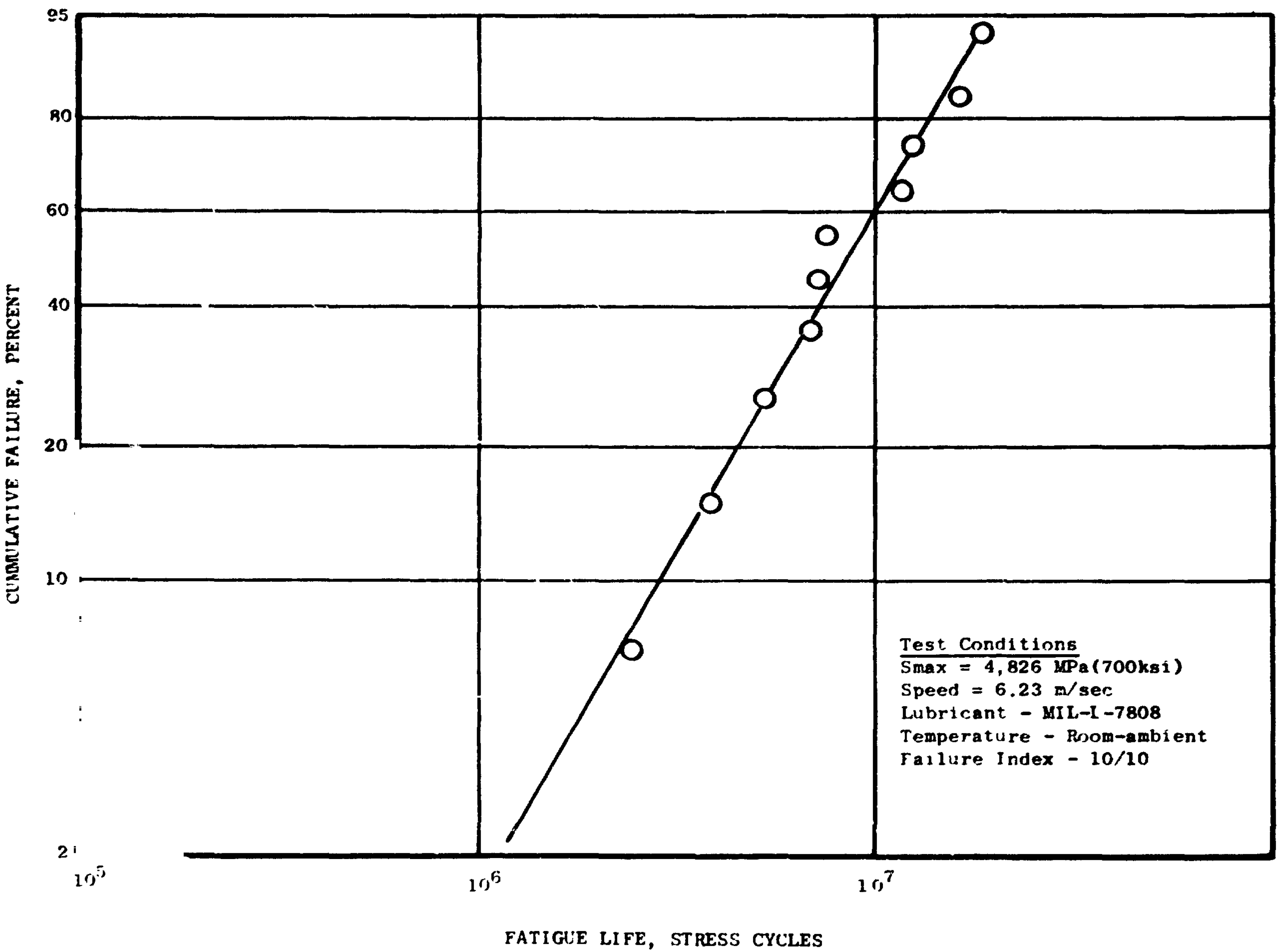

Figure 36. RCF Test Results of VAR VASCO X-2, (Test Series AJ)

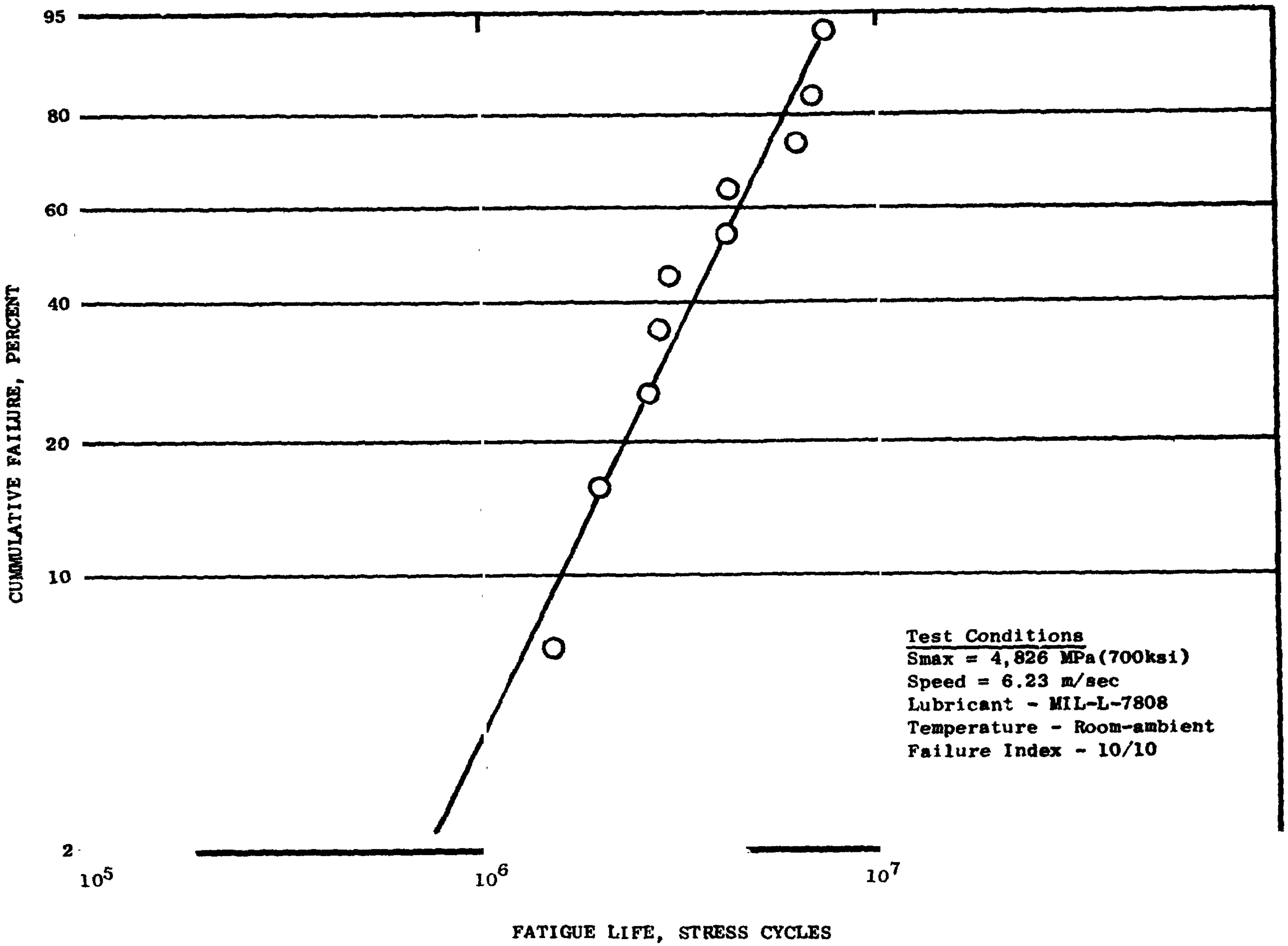

Figure 37. RCF Test Results of VAR VASCO X-2, Tempered at 510°C (Test Series AK)

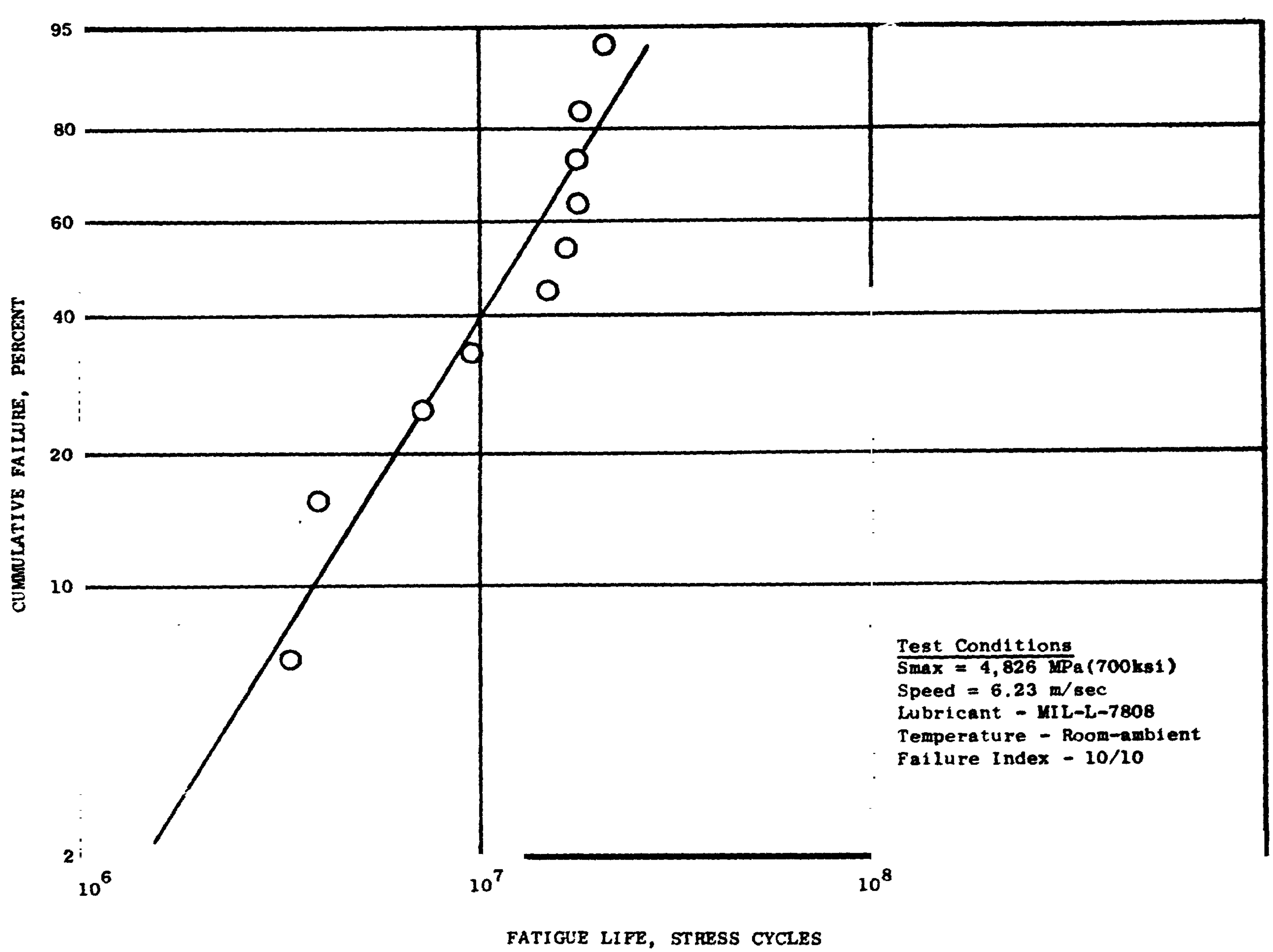

Figure 38. RCF Test Results of VAR VASCO X-2, Tempered at 316°C, (Test Series AL)

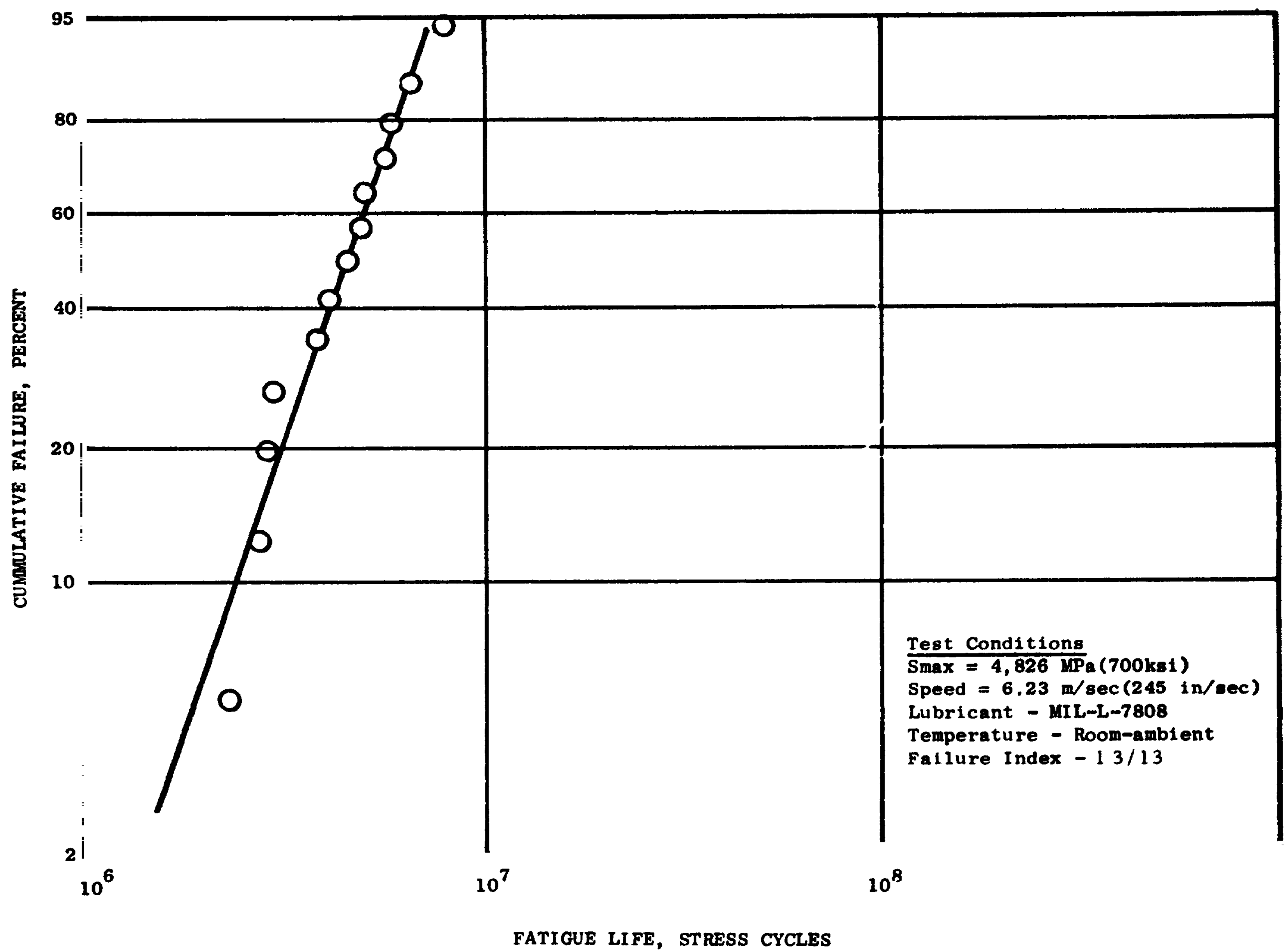

Figure 39. RCF Test Results of VAR VASCO X-2, Tempered at 316°C (shot-peened, Test Series AM)

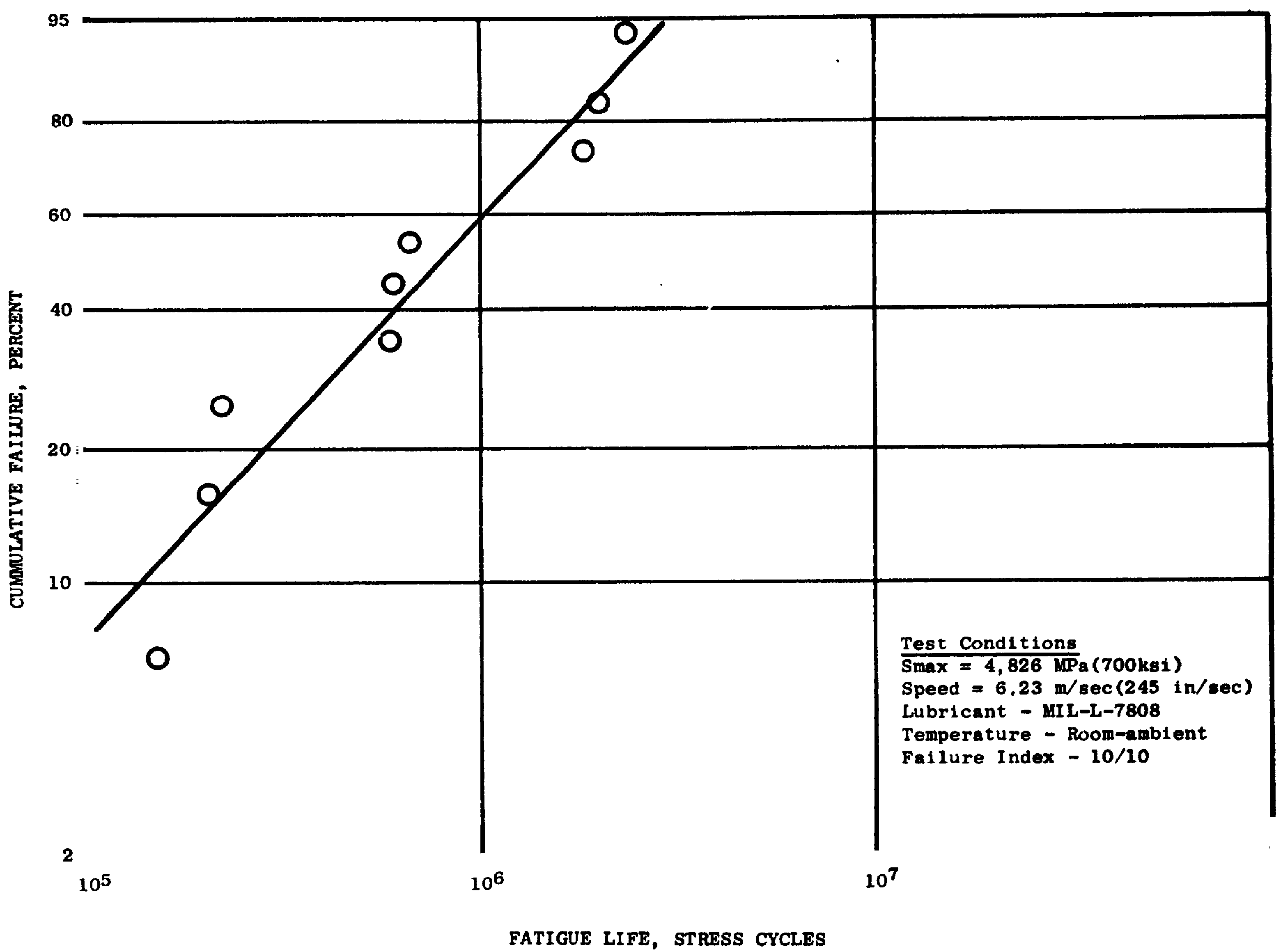

Figure 40. RCF Test Results of VAR VascoMax 350 (Test Series AN)

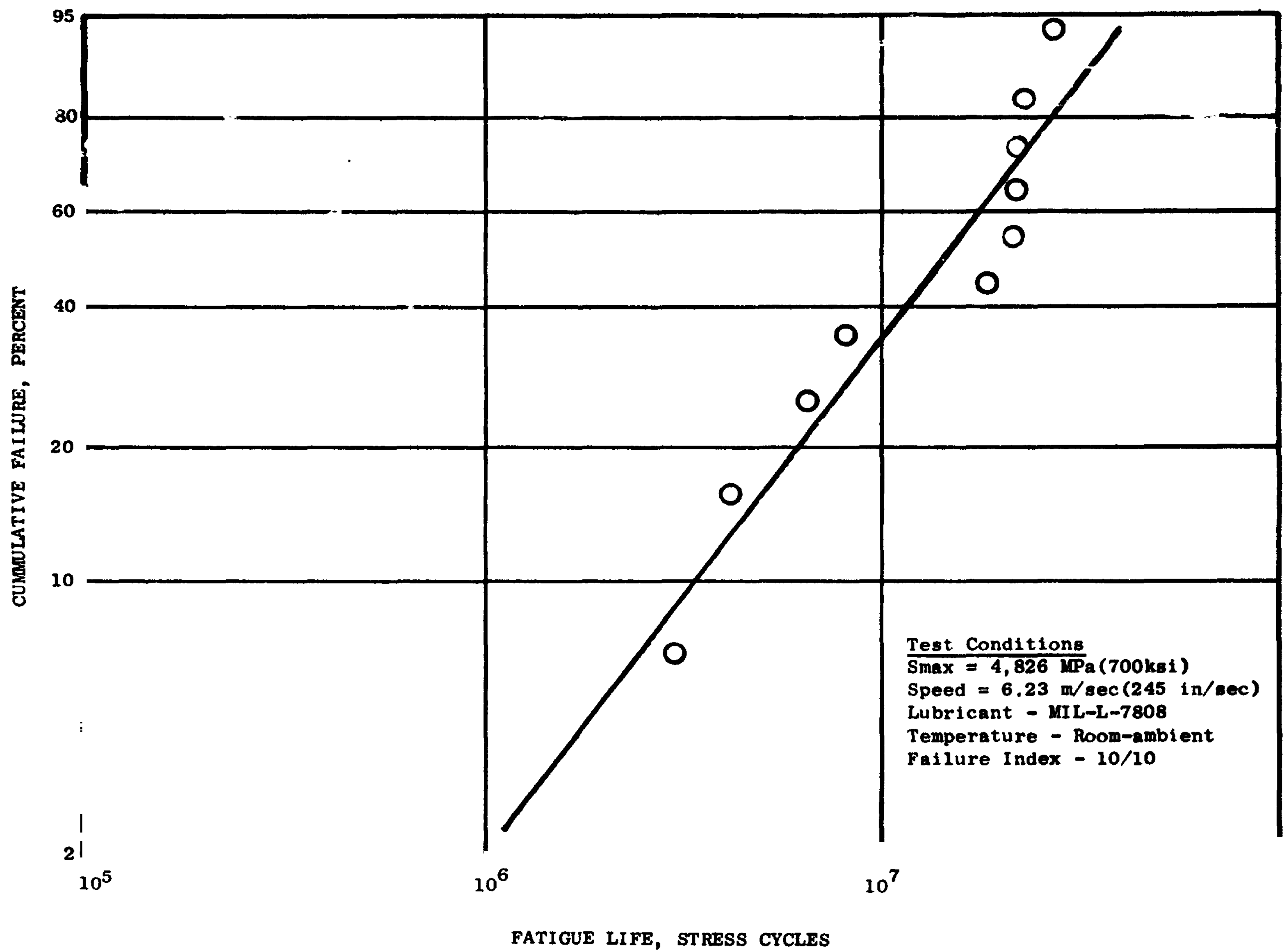

Figure 41. RCF Test Results of VAR Vasco Matrix II (Test Series AO)

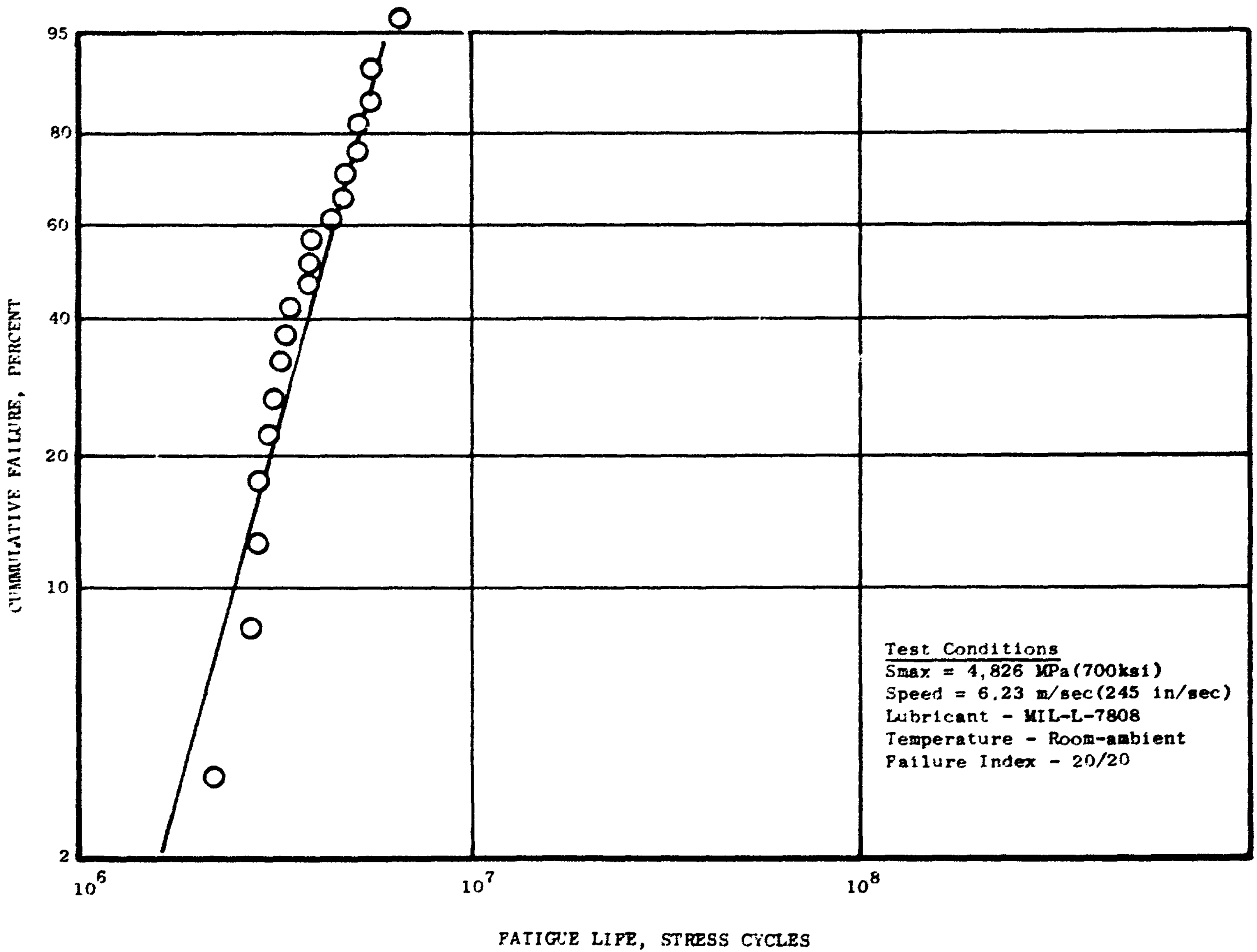

Figure 42. RCF Test Results of VAR AISI M-50 (Test Series AP)

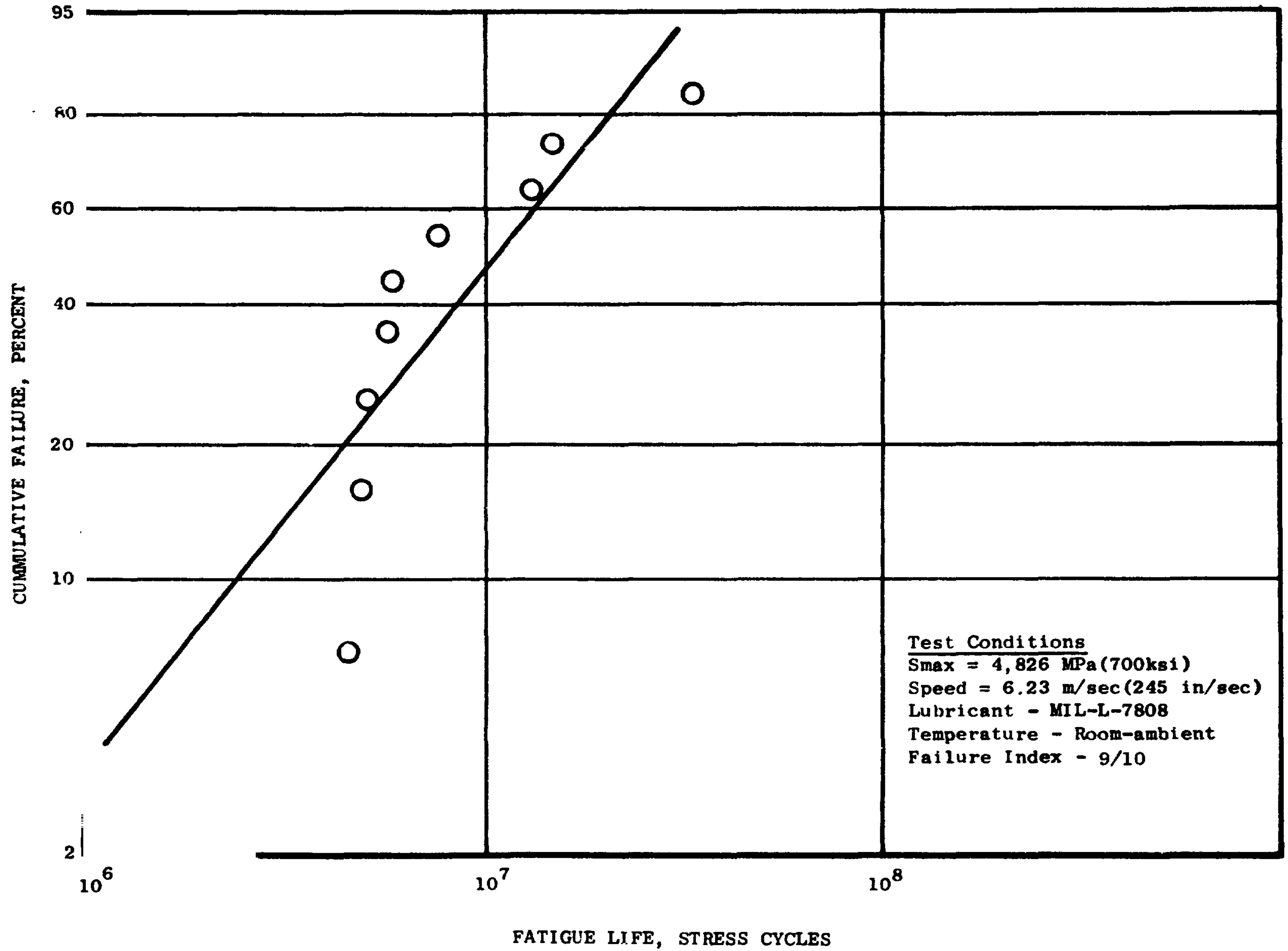

Figure 43. RCF Test Results of VAR AISI 9310 (Test Series AQ)

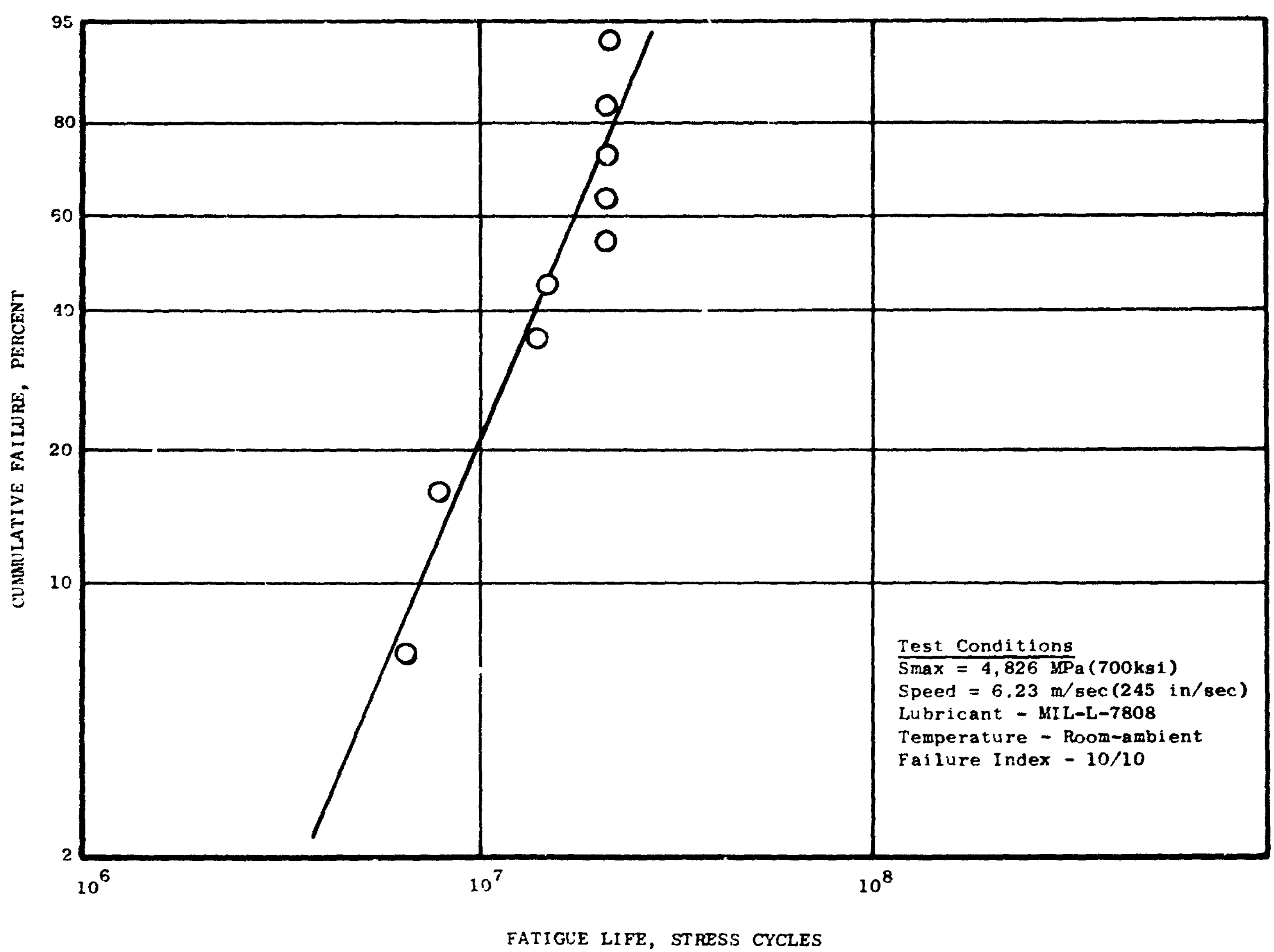

Figure 44. RCF Test Results of VIM-VAR 9310 (Test Series AR)

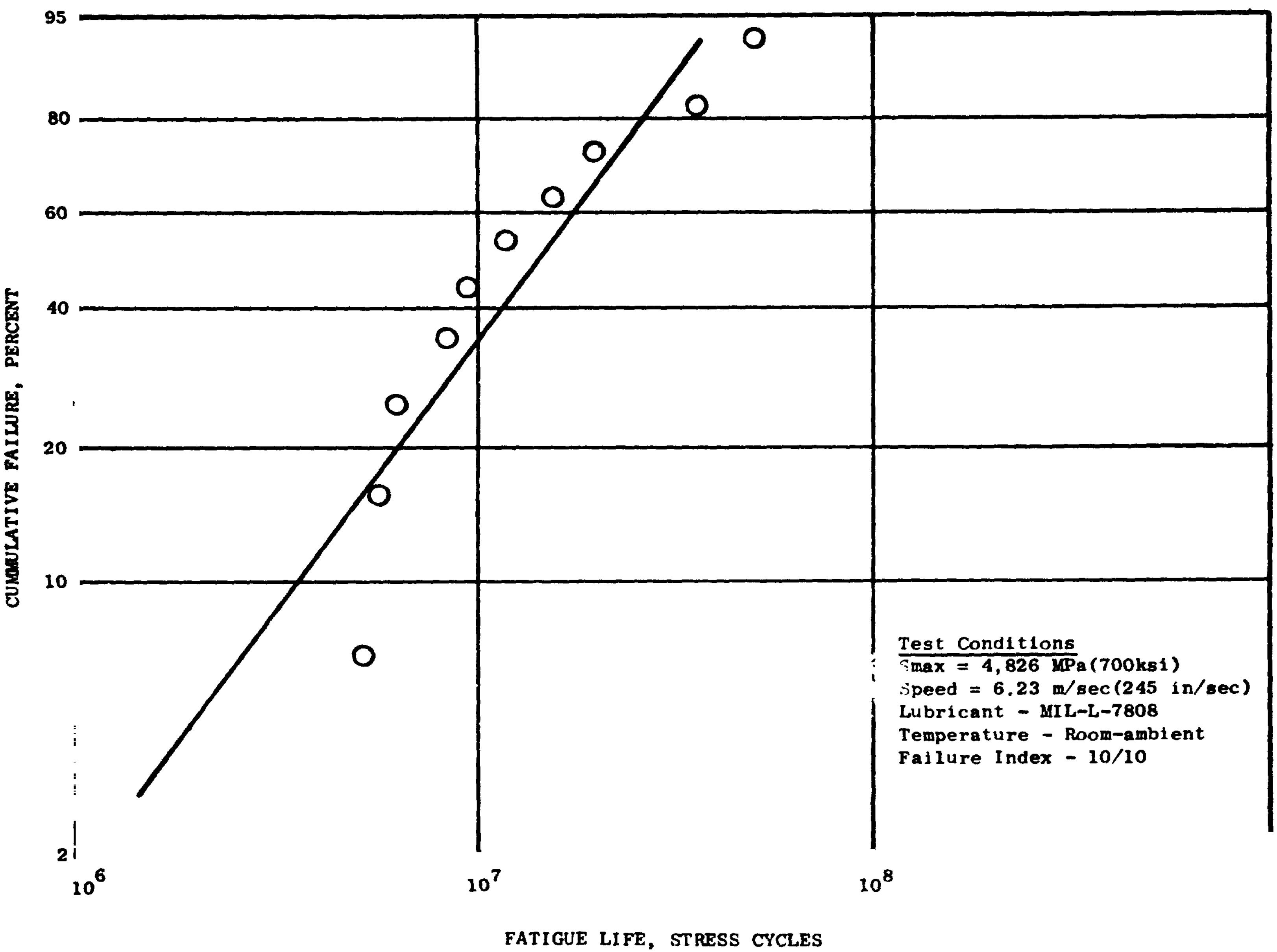

Figure 45. RCF Test Results of VAR EX00014 (Test Series AS)

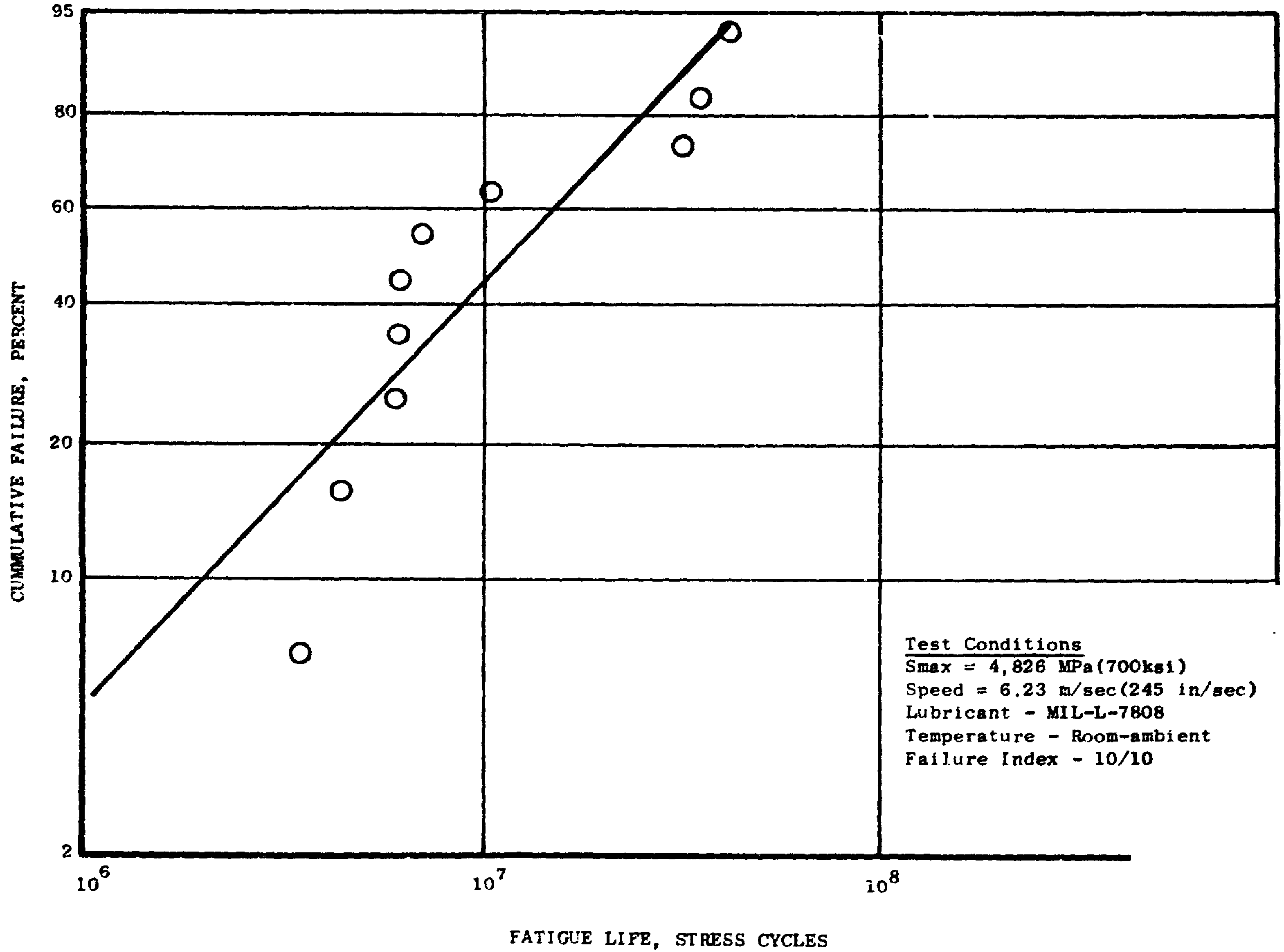

Figure 46. RCF Test Results of VAR EX00053 (Test Series AT)

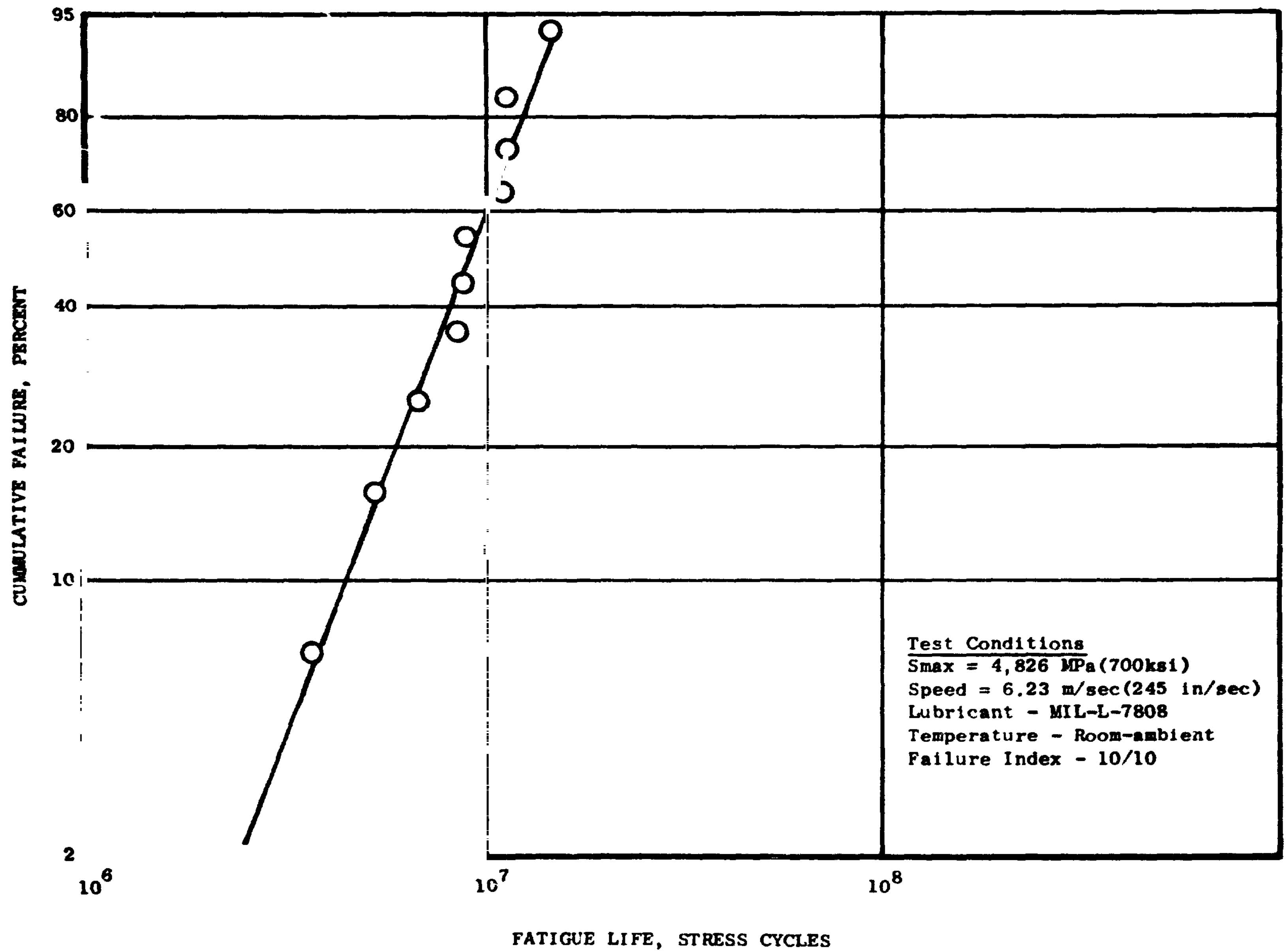

Figure 47. RCF Test Results of VIM-VAR AISI M-50 (gold plated, Test Series AU)

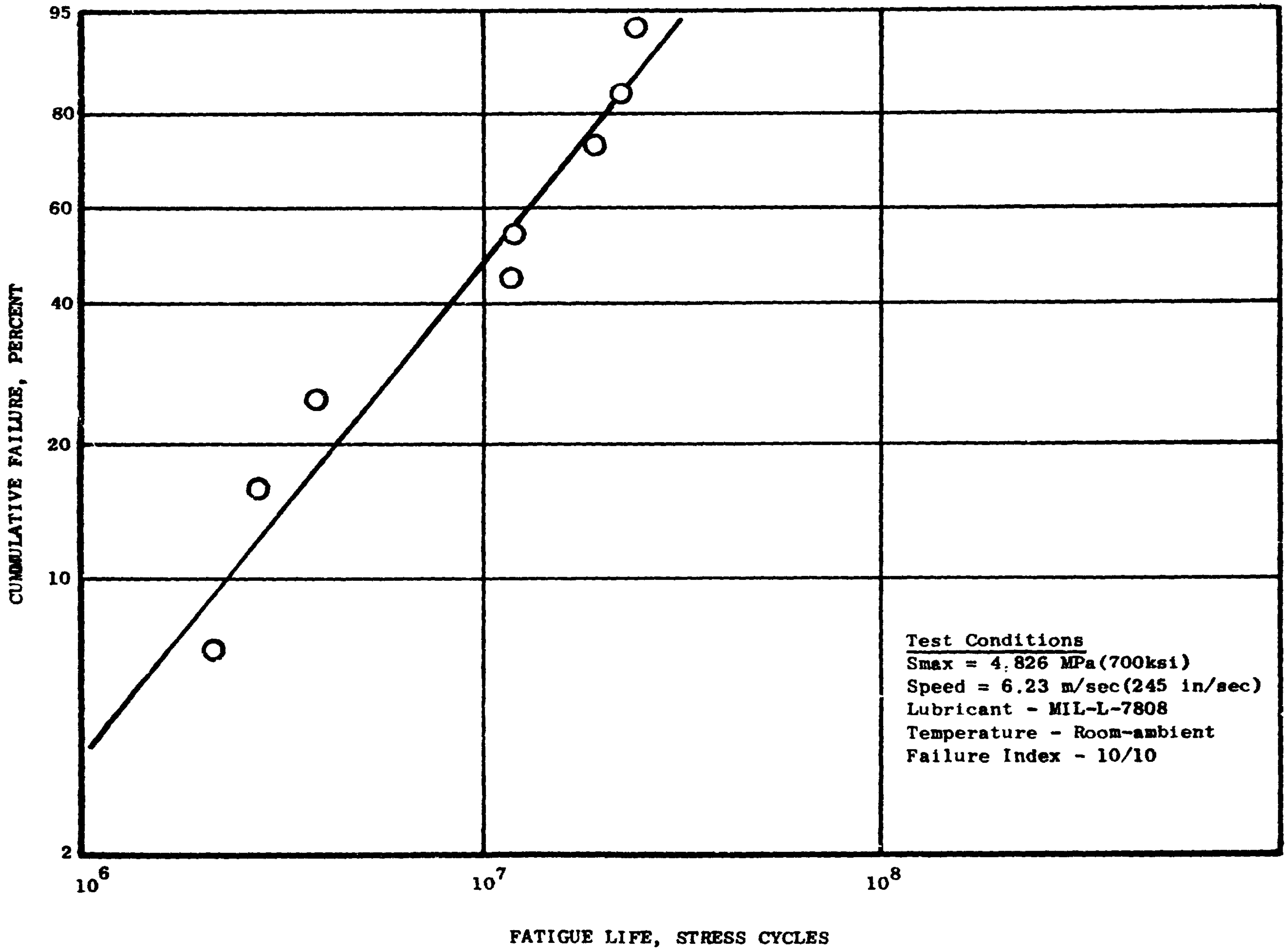

Figure 48. RCF Test Results of VIM-VAR AISI M-50 (chrome-plated, Test Series AV)

APPENDIX E

TABLE 45

SUMMARY OF RCF TEST RESULTS AND METALLURGICAL CHARACTERISTICS OF TEST MATERIALS FOR PHASE III

Test Series	Test Materials (Melting Process)	B-10 Life, 10^6 Cycles	B-50 Life, $\times 10^6$ Cycles	Weibull Slope	Failure Index	Effective Case Depth mm (in.)	Surface Hardness HRC	Core Hardness HRC	Case Retained Austenite Vol. %	Remarks
AG	AISI M-50 (VIM-VAR)	3.34	7.77	2.23	27/27	--	63.0	--	N.D.	Replaces Nitralloy N
AH	CBS600 (AM)	1.91	7.31	1.40	10/10	0.76 (0.030)	62.9	41.0	22.8	
AI	CBS1000M (VAR)	2.08	4.36	2.55	10/10	0.89 (0.035)	61.4	47.0	N.D.	
AJ	Vasco X-2 (VAR)	2.88	8.55	1.73	10/10	0.76 (0.030)	61.8	42.0	5.0	316°C (600°F) temper
AK	Vasco X-2 (VAR)	1.56	3.93	2.03	10/10	0.76 (0.030)	60.5	46.0	N.D.	510°C (950°F) temper
AL	Vasco X-2 (VAR)	3.63	12.24	1.55	10/10	0.64 (0.025)	60.6	43.0	11.0	316°C (600°F) temper
AM	Vasco X-2 (VAR)	2.30	4.42	2.89	13/13	0.64 (0.025)	62.4	43.0	11.0	316°C (600°F) temper, shot peened
AN	VascoMax 350 (VAR)	0.14	0.77	1.09	10/10	--	59	--	N.D.	Age hardened

TABLE 45

SUMMARY OF RCF TEST RESULTS AND METALLURGICAL CHARACTERISTICS OF TEST MATERIALS FOR PHASE III (Continued)

Test Series	Test Materials (Melting Process)	B-10 Life, $\times 10^6$ Cycles	B-50 Life, $\times 10^6$ Cycles	Weibull Slope	Failure Index	Effective Case Depth mm (in.)	Surface Hardness HRC	Core Hardness HRC	Case Retained Austenite Vol. %	Remarks
AO	Vasco Matrix II (VAR)	3.31	13.89	1.31	10/10	--	61.8	--	N.D.	
AP	AISI M-50 (VAR)	2.46	4.01	3.85	20/20	--	60.6	--	N.D.	
AQ	AISI 9310 (VAR)	2.25	10.63	1.21	9/10	0.51 (0.020)	60.9	42.0	16.1	Replaces REX 729
AR	AISI 9310 (VIM-VAR)	6.84	1[illegible].74	2.26	10/10	0.64 (0.025)	61.0	42.0	7.7	
AS	EX00014 (VAR)	3.27	13.85	1.31	10/10	0.51 (0.020)	60.6	42.0	5.5	
AT	EX00053 (VAR)	1.95	11.6	1.06	10/10	0.64 (0.025)	62.0	36.0	4.8	
AU	AISI M-50 (VIM-VAR)	4.21	8.88	2.53	10/10	--	63.0	--	N.D.	Gold Plated
AV	AISI M-50 (VIM-VAR)	2.28	10.66	1.22	10/10	--	63.0	--	N.D.	Chrome Plated
Base-line	AISI M-50 (VIM-VAR)	3.80	6.30	3.30	250/250	--	63.0	--	N.D.	
Base-line	AISI 9310 (VAR)	4.18	9.43	2.31	10/10	0.84 (0.033)	61.4	38.0	11.2	