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ROLLING ELEMENT FATIGUE TESTING OF GEAR MATERIALS

INTERIM REPORT

by

A.H. NAHM

GENERAL ELECTRIC COMPANY

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16. Abstract

Rolling element fatigue lives of elevent alloys were evaluated using the General Electric Rolling Contact Fatigue (RC) rigs. The eleven alloys studied were three nitriding alloys (Super Nitralloy, Nitralloy 135, and Nitralloy N), four case carburizing alloys (AISI 9310, CBS 600, CBS 1000M and Vasco X-2), and four through-hardening alloys (Vasco Matrix II, AISI W-1, AISI S-2 and AISI O-2). Several different heat treatments and/or melting processes have been studied on the three carburizing alloy steels. 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 rates) [illegible]pared versus VIM-VAR AISI M-50 and carburized VAR AISI 9310, as reference alloys.

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FOREWORD

This program was conducted by the Material & 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 author acknowledges the valuable guidance of Messrs. E.N. Bamberger and F.C. Robertshaw during the entire course of the investigation. The Technical Project Manager for GE was Mr. D.B. Hester. The contributions of Mr. D.J. Kroeger, who performed the testing and evaluation essential in this study, are also gratefully acknoledged.

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I. INTRODUCTION

General Electric Company, under Contract to NASA-Lewis Research Center, has been conducting a 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 aircrafts.

AISI 9310 has been most widely used as a standard aviation gear 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 and reliability at elevated temperature (200° C +). 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.

Since there has not been a systematic evaluation of rolling element fatigue life performance on various alloys including newly developed materials, a major part of this effort has been to study the rolling contact fatigue behavior under uniform, carefully controlled experimental conditions.

The earlier phases of this study were concerned primarily with evaluating the rolling element fatigue characteristics and failure modes of hollow rolling elements. Included therein were investigations of through-hardened and case carburized materials having various OD/ID wall thickness ratios.(1) Additionally, work was also performed establishing the effect of different material combinations on rolling element fatigue. These efforts comprising of Tasks I through VIII of subject contract, have been successfully completed and have been reported.(2)

The purpose of this interim report is to document the work covered in Tasks IX through XIII (February 1975 through April 1977) of the subject contract (NAS3-14302). The Tasks IX through XIII deal with the rolling element fatigue testing and subsequent metallurgical analysis of gear materials. Rolling element fatigue lives of eleven alloys were evaluated in Phase I. The effects of different heat treating processes and additional vacuum melting processing on the fatigue life of several carburizing alloys were studied in Phase II. The results are compared with the standard aviation alloys for bearings and gears, AISI M-50 and AISI 9310, respectively.

II. EXPERIMENTAL

Eleven alloys were tested in the General Electric Rolling Contact (RC) Fatigue Test rigs. Several different heat treatments and/or melting processes have been studied on some of the eleven alloys. Metallurgical analyses were made before and after the RC rig tests. Fatigue test data were analyzed statistically using the Weibull distribution function. The experimental details are described in the following.

a) Test Materials

Eleven materials were tested in 17 test series as follows:

PHASE I

Test Series	Materials	Hardening Process
u	CVM* Super Nitralloy	Case nitriding
v	AM**Nitralloy 135	Case nitriding
w	CVM Vasco Matrix II	Through-hardening
x	CVM AISI 9310	Case carburizing
y	CVM CBS 600	Case carburizing
z	CVM CBS 1000M	Case carburizing
α	CVM AISI W-1	Through-hardening
β	CVM AISI O-2	Through-hardening
γ	CVM AISI S-2	Through-hardening
δ	CVM Vasco X-2	Case carburizing
ε	CVM Nitralloy N	Case nitriding

PHASE II

Test Series	Materials	Hardening Process
AA	VIM-VAR***AISI 9310	Case carburizing
AB	CVM CBS 1000M	Case carburizing
AC	CVM CBS 1000M	Case carburizing
AD	CVM CBS 600	Case carburizing
AE	CVM CBS 600	Case carburizing
AF	CVM CBS 600	Case carburizing

*CVM - Consumable vacuum melted. CVM is also called as VAR (Vacuum arc remelted).

**AM - Air melted.

***VIM-VAR - Vacuum induction melted and vacuum arc remelted.

b) Rolling Contact Fatigue Testing

Rolling contact fatigue tests were conducted in the General Electric Rolling Contact (RC) Fatigue Test Rigs. These RC 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 testing procedure is described in General Electric Specification E50TF49 and also in Reference 3.

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 19.1 cm (7.5 in.) diameter rollers with a crown radius of 0.64 cm (0.25 in.) against a cylindrical test bar [7.62 cm (3.0 in.) long, 0.952 cm (0.375 in.) diameter]. 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-7808G) oil is supplied to the contacting surfaces, between rollers and specimen by drip feeding approximately 20 drops per minute. Physical property data of the lubricant are given in Appendix A.

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

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

where σ_1 and σ_2 are the surface roughnesses of the mating parts. However, the surface roughnesses rapidly change to smoother surfaces after a short period of testing time. Consequently, the composite surface roughness is assumed to equilibrate to 0.18 μm (7 μin.) rms.

Cheng's formula[4] was used to calculate the minimum oil film thickness, h_{min}. Assuming the temperature of lubricant in the contact area to be 38° C (100° F), the film thickness is 0.21 μm (8.3 μin.). Therefore, the specific film thickness ratio $\frac{h_{min}}{\sigma_c}$ is estimated to be about 1.2. This is considered to be partial elastohydrodynamic lubrication, 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 CBS 600 is shown in Figure 3 as an example.

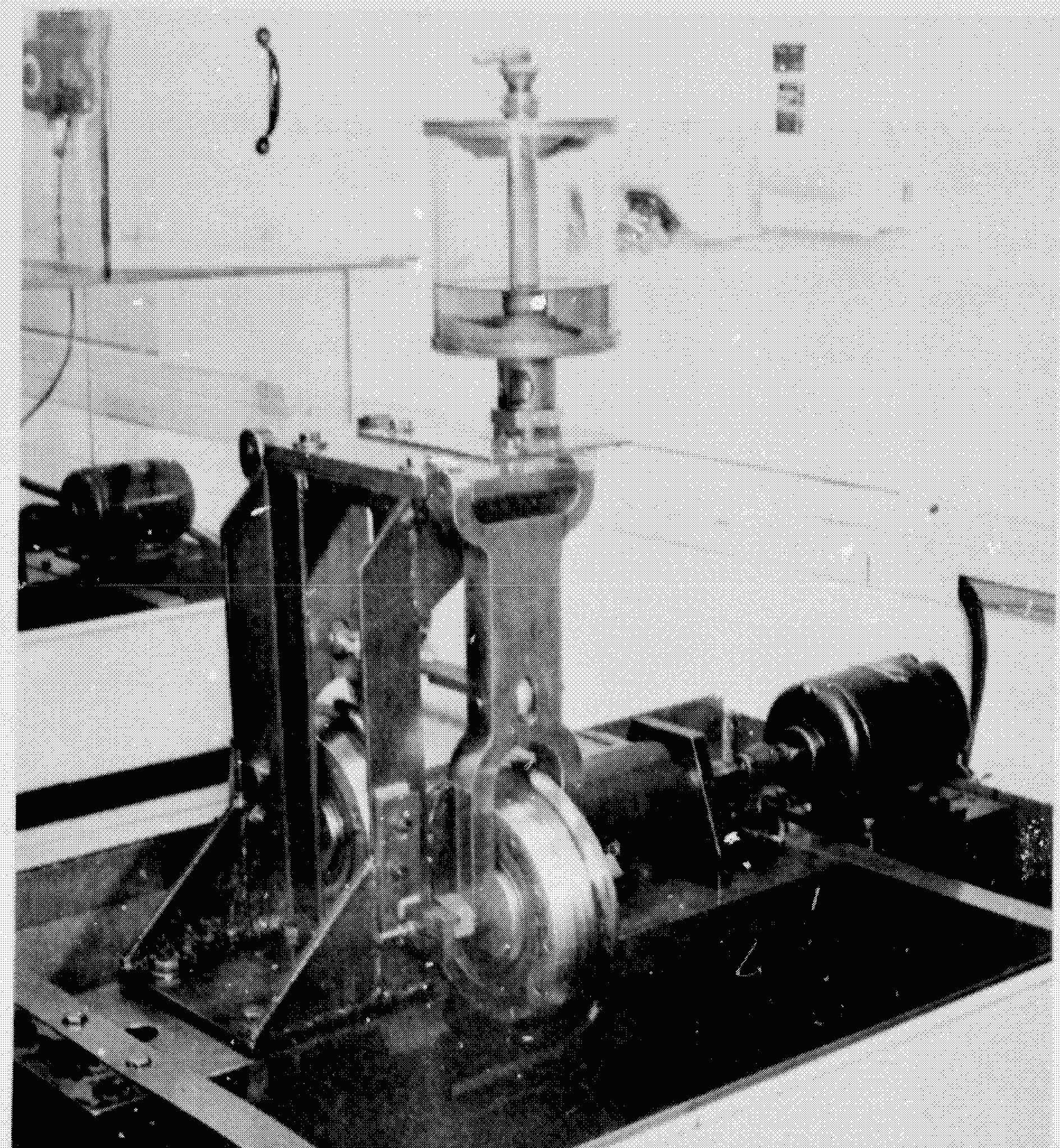

Figure 1. Overview, GE RC Ri

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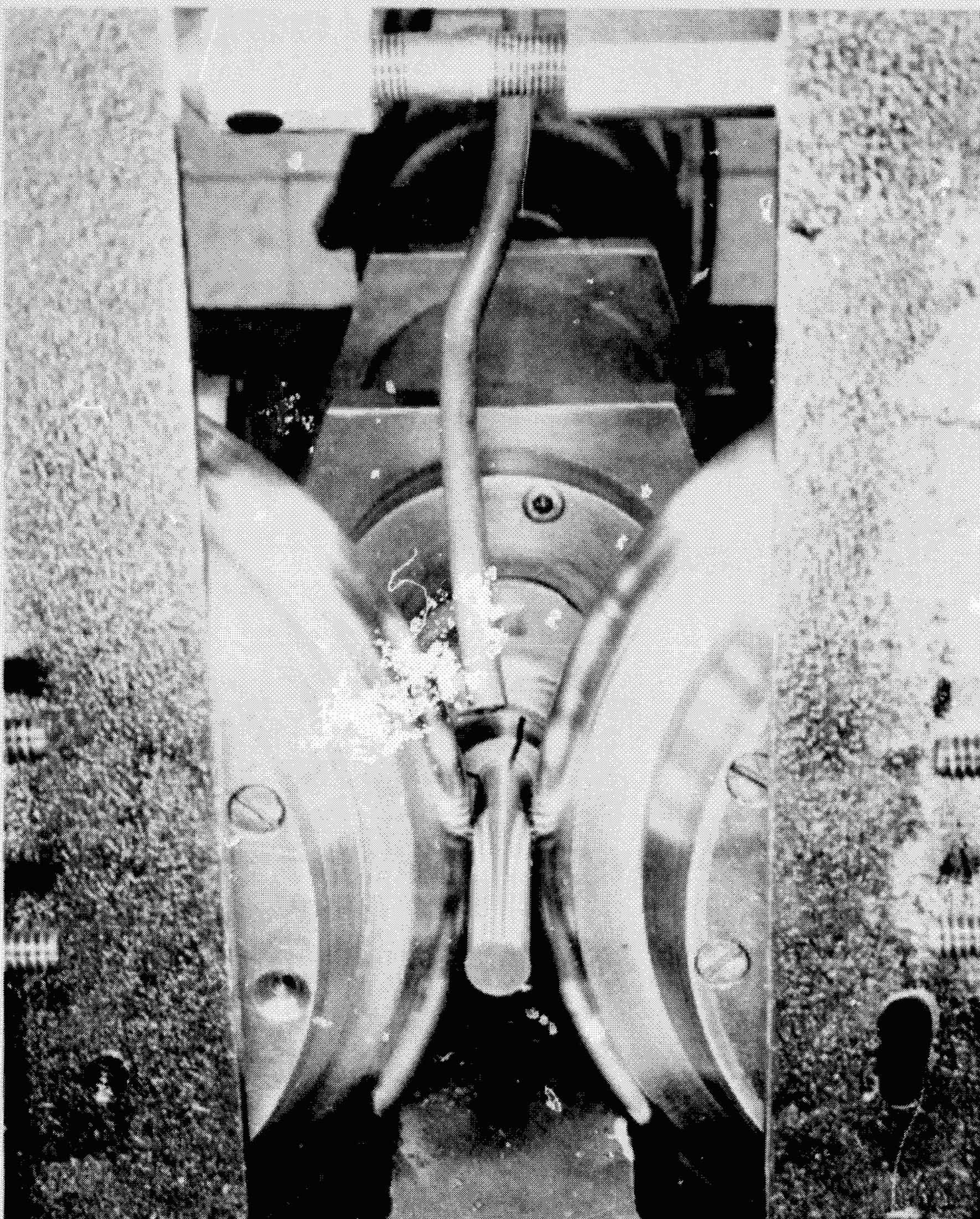
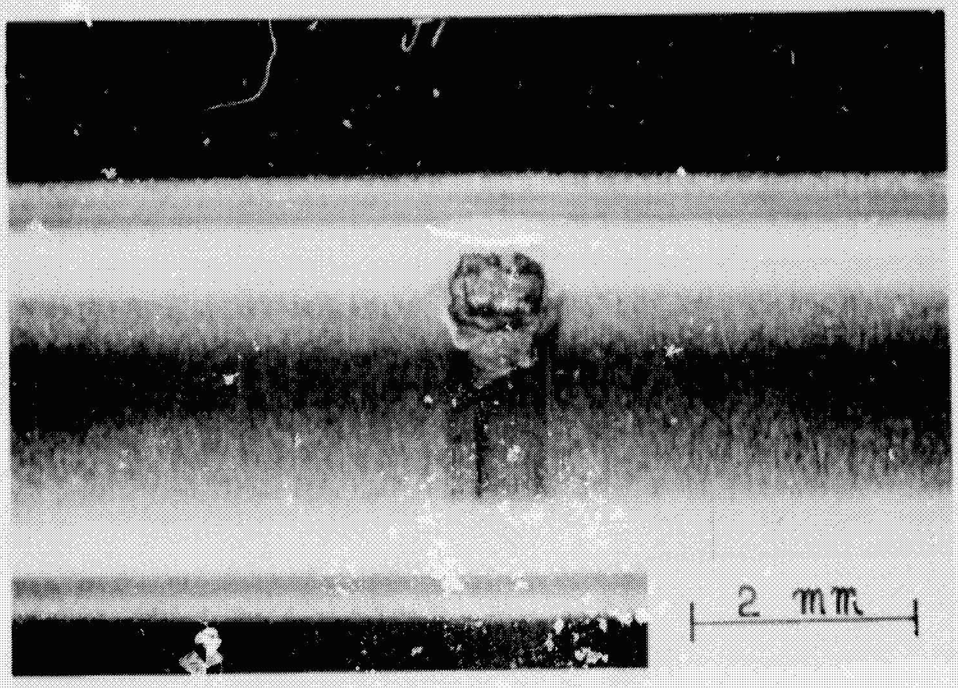


Figure 2. Closeup, Specimen and Roller Geometry in RC Rig.



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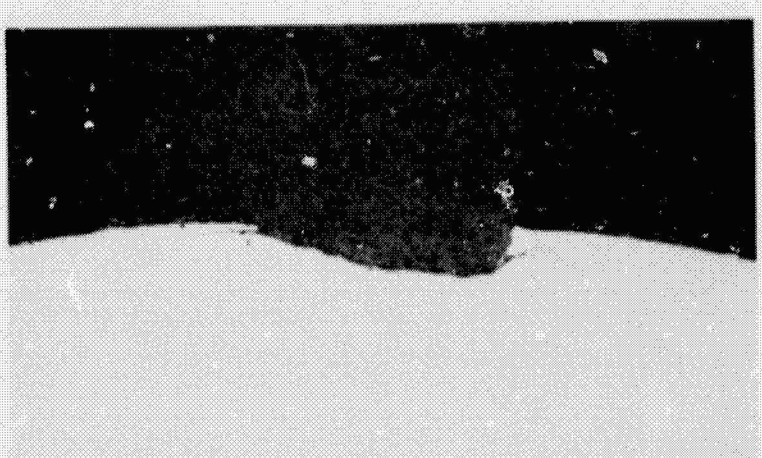

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Figure 3. Typical Rolling Contact Fatigue Failure in CBS 600.

c) <u>Metallurgical Evaluation of Test Materials</u>

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. 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.

d) <u>Fatigue Data Analysis</u>

Rolling contact fatigue data were analyzed in the Weibull distribution function and statistically considered in a manner suggested by Johnson.[5] The fatigue life in number of stress sycles 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 by spalling. 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 all tests series and of VAR AISI 9310, as a baseline, are presented in Appendix B. Corresponding Weibull plots are also included in Appendix B. Appendix C represents a summary of test results for Phase I and II in which B-10 life, B-50 life, Weibull slope and failure index are given. The failure index is defined as number of failures out of total number of tests performed. Data for VIM-VAR AISI M-50 are also included in Appendix C as baseline. These are based on more than 250 tests from 12 different heats which were heat treated to HRC 63±1. A summary of metallurgical characteristics for Phase I and II test materials is given in Appendix D.

For convenience, this chapter is divided into five sections as follows:

a) AISI 9310
b) CBS 600
c) CBS 1000M and Vasco X-2
d) Nitriding alloys
e) Through-hardening alloys

The results described in Appendices are rearranged accordingly.

a) AISI 9310

Chemical compositions of AISI 9310 used in this investigation are given in Table 1. Table 2 gives the details of the heat treating process used for AISI 9310. As shown in Table 2, Test Series AA and baseline were heat treated at the same time under identical conditions. The main object therein was to find the effect of double vacuum melting (VIM-VAR) versus single vacuum melting (CVM) on rolling element fatigue life of AISI 9310.

Table 3 shows RCF test results and the Weibull plots of the results are presented in Figure 4. B-10 lives are also indicated as a bar chart in Figure 5.

Optical photomicrographs showing case and core microstructures of Test Series x and AA are given in Figures 6 and 7. No noticeable differences in optical microstructure were found between VIM-VAR AISI 9310 (Test Series AA) and VAR AISI 9310 (baseline). Figure 6-(a) clearly shows that high retained austenite is present in the case microstructure of Test Series x specimens (compare with Figure 7-(a)). The retained austenite is seen as unetched white background phase. A summary of metallurgical analysis of AISI 9310 test series is given in Table 4. Variations of the amount of retained austenite present in the case structure were measured to be 8.3%, 11.2% and 20.1% for Test Series AA, baseline, and x respectively. Retained austenite and melting process seem to be the only significant variables influencing rolling contact fatigue life behavior of AISI 9310 under the present experimental conditions (see Table 4). Differences among all the other important variables, for example, hardness, effective case depth, etc., are minimal.

Table 1. Chemical Composition of AISI 9310.

Test Series	Test Materials	Alloying Element, percent by weight (balance Fe)								
		C	Si	Mn	S	P	Cr	Mo	Ni	Cu
X	VAR AISI 9310	0.07	0.13	0.63	0.007	0.007	1.32	0.13	3.24	0.11
AA	VIM-VAR AISI 9310	0.11	0.31	0.52	0.014	0.006	1.25	0.12	3.14	0.16
Baseline	VAR AISI 9310	0.11	0.31	0.63	0.012	0.005	1.24	0.11	3.19	0.07

Table 2. Heat Treating Process for AISI 9310.

	Test Materials (Test Series)		
Heat Treating	VAR AISI 9310 (A)	VIM VAR AISI 9310 (AA)	VAR AISI 9310 (baseline)
Preheat	927° C (1700° F) 15 minutes, AC to RT		
Carburize	927° C (1700° F)	941° C-968° C (1725° F-1775° F) 12 hours	
Reheat		593° C (1100° F) 10 hours, air cool	
Austenitize	857° C (1575° F) oil quench	857° C (1575° F) 20 minutes, oil quench	
Deep Freeze	-73° C (-100° F) 3 hours	-73° C (-100° F) 3 hours	
Temper	182° C (360° F) 1 hour	182° C (360° F) 1 hour	

Table 3. Summary of RCF Test Results of AISI 9310.

Test Series	Melting Process	B-10 Life, X 10^6 cycles	B-50 Life, X 10^6 cycles	Weibull Slope	Failure[a] Index
x	VAR	14.82	61.50	1.32	6/20
AA	VIM-VAR	5.25	10.65	2.66	10/10
Baseline	VAR	4.18	9.43	2.31	10/10

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

Test Conditions:

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

Table 4. Metallurgical Characteristics of AISI 9310.

Test Series	Melting Process	Effective Case Depth, mm (in)	Case Hardness, HRC	Core Hardness, HRC	Retained Austenite, %
x	VAR	0.76 (0.030)	60.4	41.0	20.1
AA	VIM-VAR	0.84 (0.033)	60.2	38.0	8.3
Base-line	VAR	0.84 (0.033)	61.4	38.0	11.2

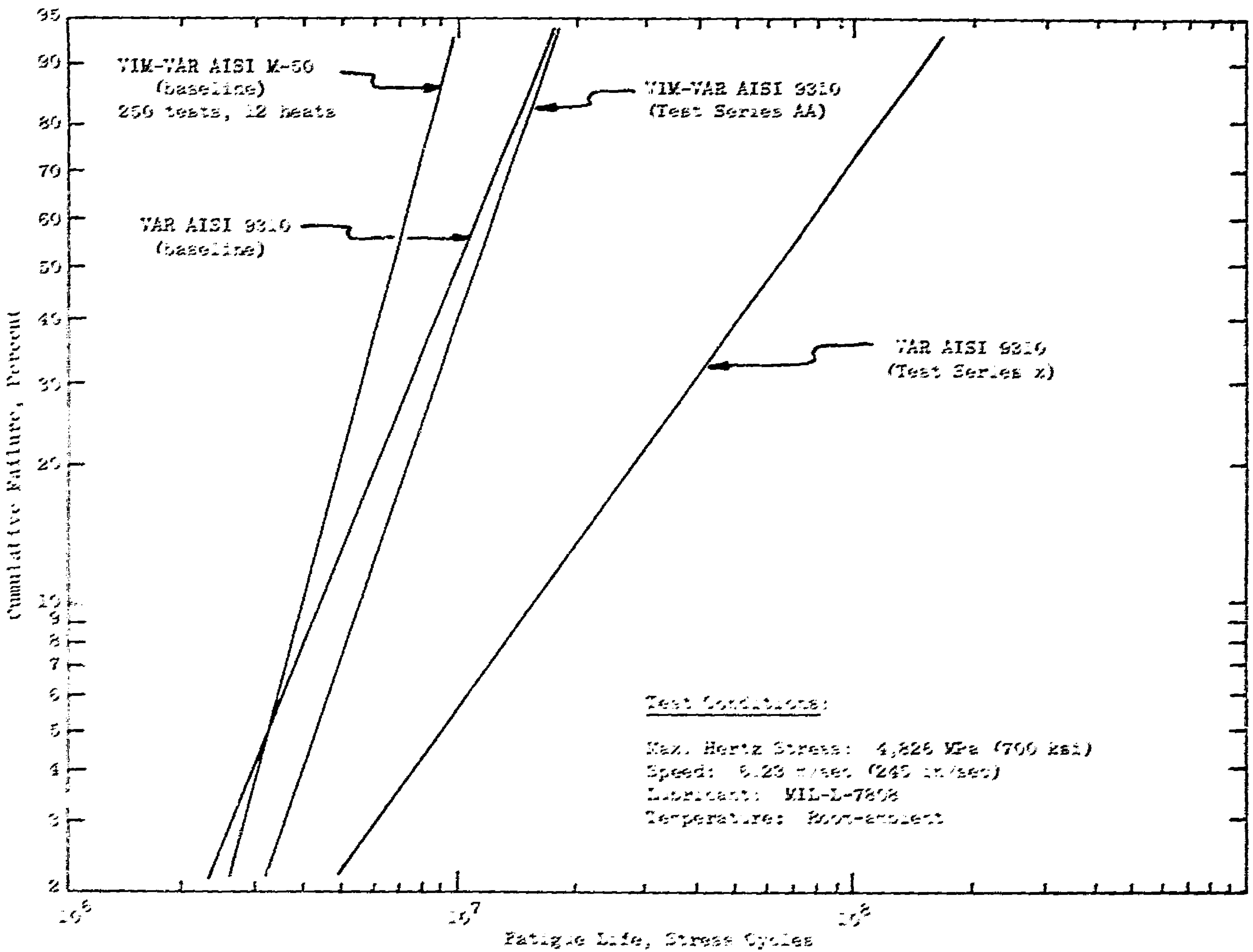


FIGURE 4. Fatigue Life Comparison of AISI 9310.

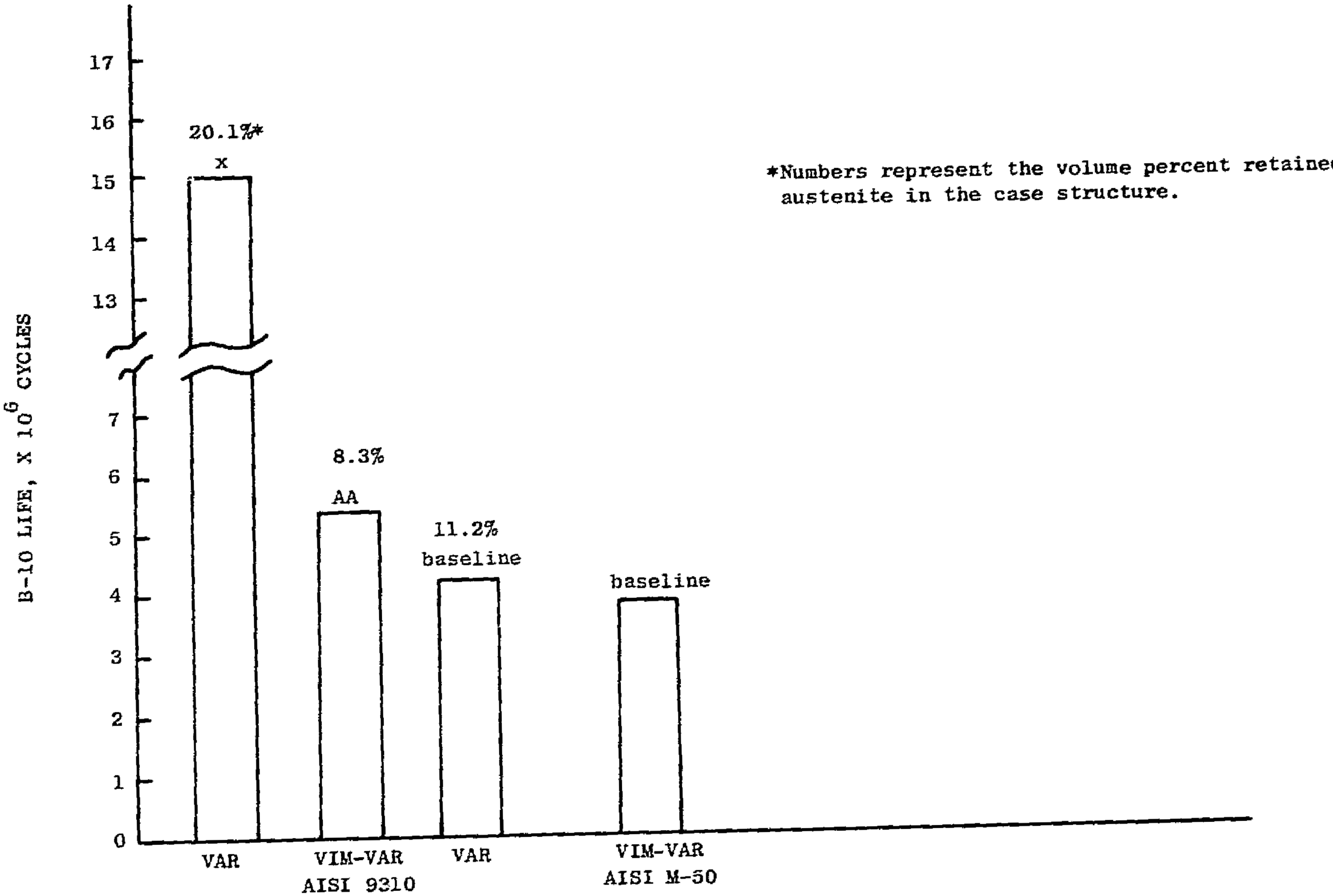
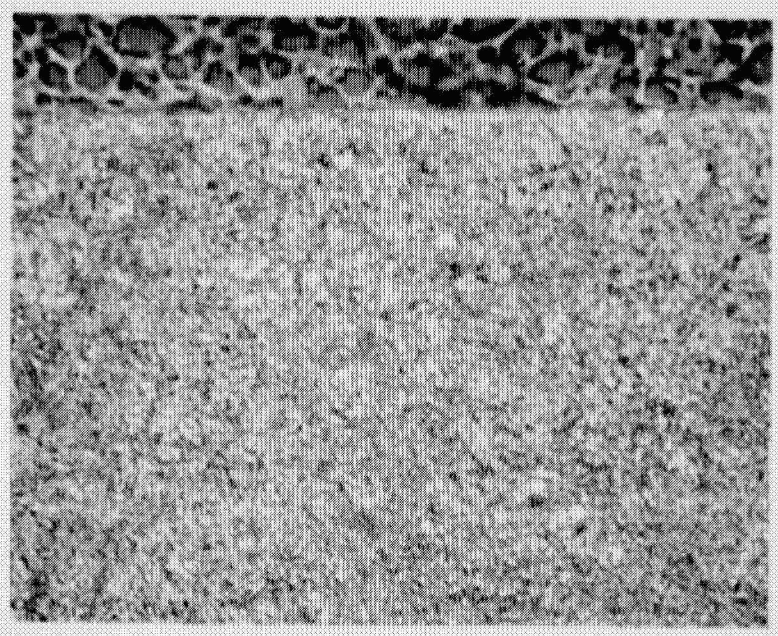


FIGURE 5. B-10 FATIGUE LIFE COMPARISON OF AISI 9310



(a)
Case

Nital Etch (b) 500X
Core

Figure 6. Optical Microstructure of AISI 9310, Test Series x.

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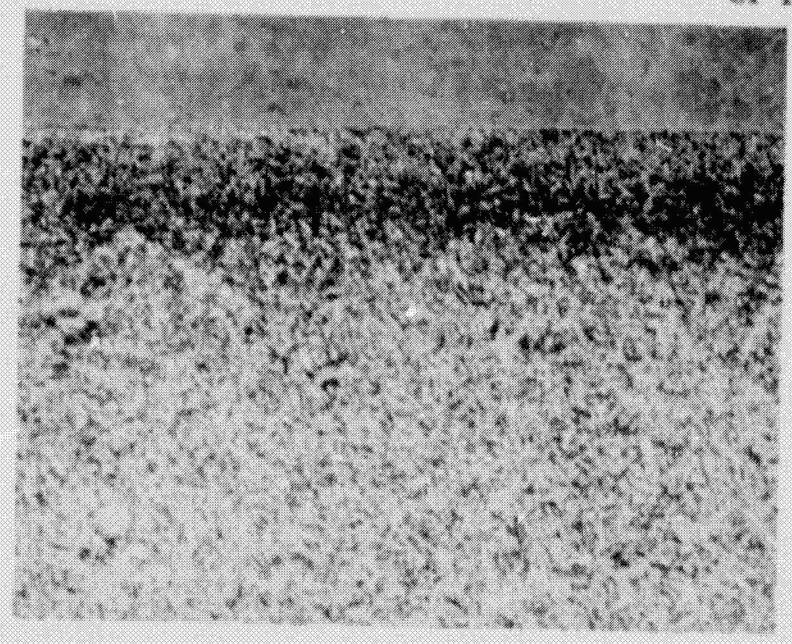


(a)
Case

Nital Etch (b) 500X
Core

Figure 7. Optical Microstructure of AISI 9310, Test Series AA.

An increase in retained austenite from 11.2% to 20.1% is accompanied by an improvement in rolling contact fatigue (more than three times) from 4.18 x 10^6 cycles to 14.82 x 10^6 cycles in B-10 life. It is interesting to note that no difference in rolling contact fatigue was found between specimens with 8.3% and 11.2% retained austenite. It may be that retained austenite must exceed 20% to show significant influence in rolling contact fatigue. This is in general agreement with Kern's report(6) that 15% to 30% retained austenite in case structure is beneficial to rolling contact fatigue of gears. It is also known that retained austenite enhances impact fatigue, high and low cycle fatigue, and toughness of materials(7-10).

Retained austenite in precision bearing is kept at minimal level (often less than 3%). This is because retained austenite is known to induce undesirable dimensional instability. Retained austenite transforms to martensite under loading or at elevated temperature, causing dimensional changes. However, in gears, it may be possible to allow some amount of retained austenite. This is due to the less stringent dimensional requirements in gear design than bearing design. The dimensional change is expected to be negligible because retained austenite exists mostly near surface case structure. It was also suggested that the transformation under loading may provide a favorable residual stress distribution against the surface fatigue damage(9).

It is also apparent that double vacuum processed AISI 9310 (VIM-VAR) does not improve significantly rolling contact fatigue life performance over single vacuum processed AISI 9310. This is in contrast to through-hardened AISI M-50 where VIM-VAR AISI M-50 has twice the rolling contact fatigue life of VAR AISI M-50. Present results also indicate that AISI 9310 is equivalent to or slightly better than VIM-VAR AISI M-50. However, the difference between VAR AISI 9310 and VIM-VAR M-50 is statistically insignificant.

b) CBS 600

Chemistry specification for CBS 600 is given in Table 5. The chemical composition of CBS 600 used in Test Series AD, AE and AF, is given in Table 6. Chemistry for Test Series y (Heat #2V 6978) is not available. Heat treating procedure for the four sets of test series are described in Table 7. It should be noted here that the heat treat procedure used for Test Series AE is that recommended by the material supplier.

Rolling contact fatigue test results are summarized in Table 8 and the summary of Weibull plots is given in Figure 8. Weibull plots of VIM-VAR AISI M-50 and VAR AISI 9310 are also included in Figure 8. Figure 9 shows B-10 lives of CBS 600, VAR AISI 9310 and VIM-VAR AISI M-50 as a histogram.

Optical photomicrographs are presented in Figures 10 through 15 to show the case and core microstructure of CBS 600. Microstructure observed in Test Series y is shown in Figures 10, 11, and 12. Core grain size is estimated to be ASTM #7 to 8. It is also noted that fine networks of small carbide particles were found to form along the prior austenite grain boundaries in the case microstructure of Test Series y (Figure 11-(a)). This is clearly shown at higher magnification (Figure 12).

Table 5. Chemistry Specification for CBS 600.

	(Weight Percent)
Carbon	0.17-0.22
Manganese	0.40-0.70
Sulfur	0.025 max.
Phosphorus	0.025 max.
Silicon	0.90-1.25
Chromium	1.25-1.65
Molybdenum	0.90-1.10
Iron	Balance

Table 6. Chemical Composition of VAR CBS 600 for Test Series AD, AE & AF. (Heat Number 2V6978)

	(Weight Percent)
Carbon	0.20
Manganese	0.50
Phosphorus	0.006
Sulfur	0.019
Silicon	1.01
Chromium	1.56
Nickel	0.21
Molybdenum	0.95
Copper	0.11
Iron	Balance

Table 7. Heat Treating Process for CBS 600.

Heat Treating \ Test Series	y	AD	AE	AF
Preheat	593° C (1100° F) 30 minutes	---	---	---
Carburize	927° C (1700° F) 6 hours	941°/968° C (1725°/1775° F) 13 hours, oil quench	Same as AD	Same as AD
Condition	---	621° C (1150° F) 4 hours, air cool	Same as AD	Same as AD
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
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

Table 8. Summary of RCF Test Results of CBS 600.

Test Series	Melting Practice	B-10 Life, x 10^6 cycles	B-50 Life, x 10^6 cycles	Slope	Failure[a] Index
Y	AM[b]	7.21	16.39	2.29	18/20
AD	VAR[c]	5.16	11.76	2.29	8/10
AE	VAR	5.81	11.01	2.95	10/10
AF	VAR	3.79	9.61	2.02	10/10

(a) Number of failures out of total number of tests.
(b) Air-melted.
(c) Vacuum arc remelted.

Test Conditions:

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

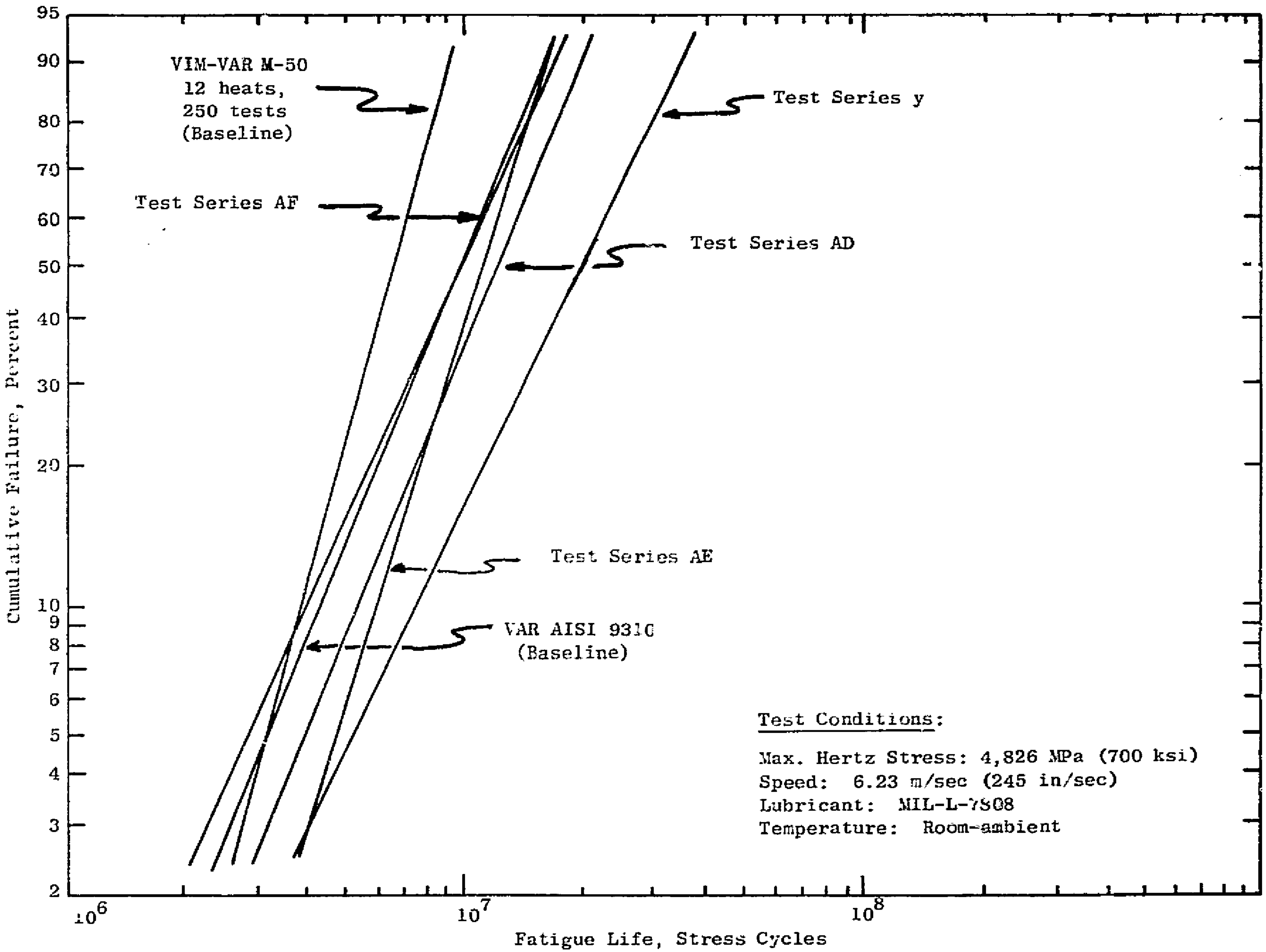


FIGURE 8. Fatigue Life Comparison of CBS 600

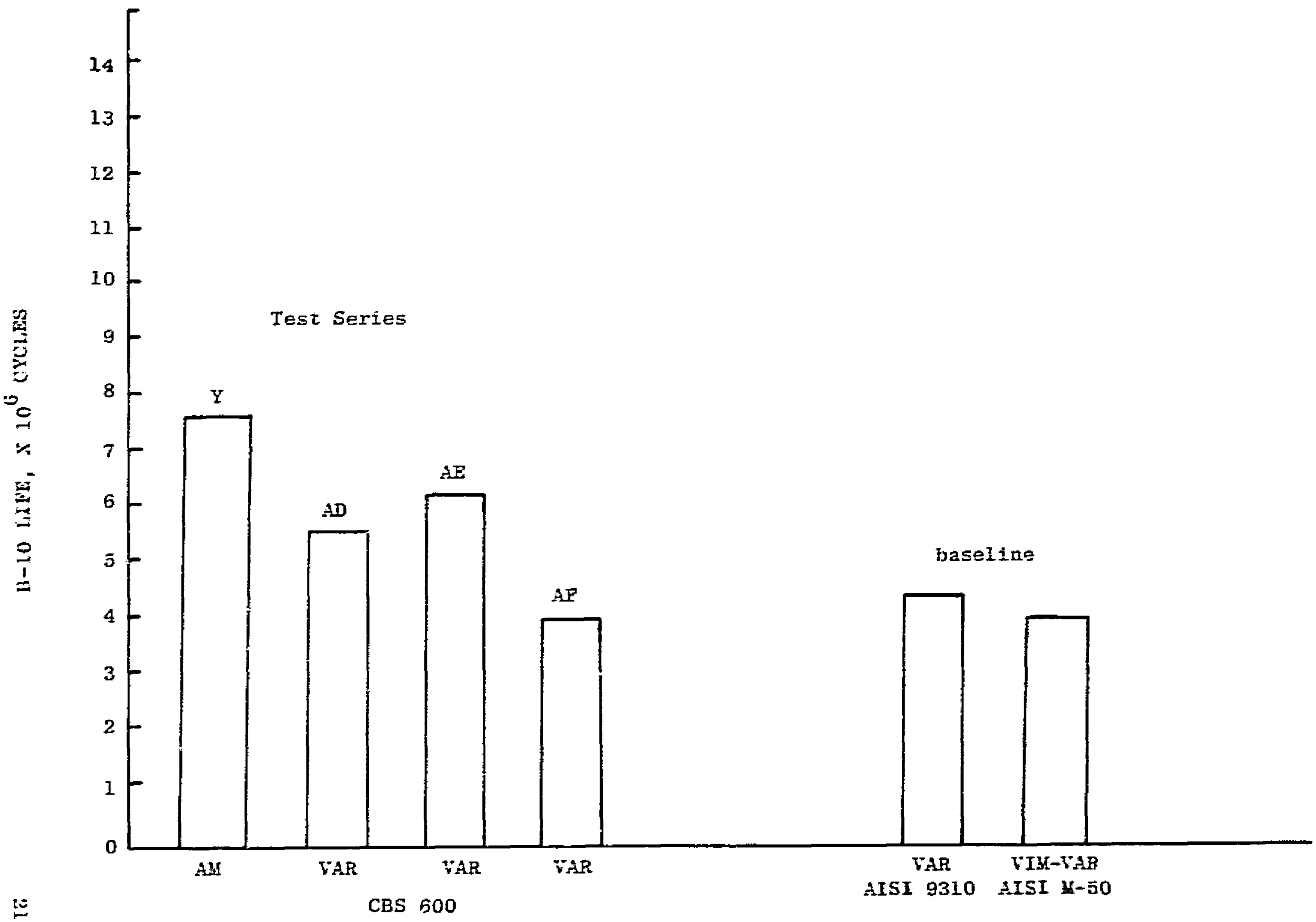
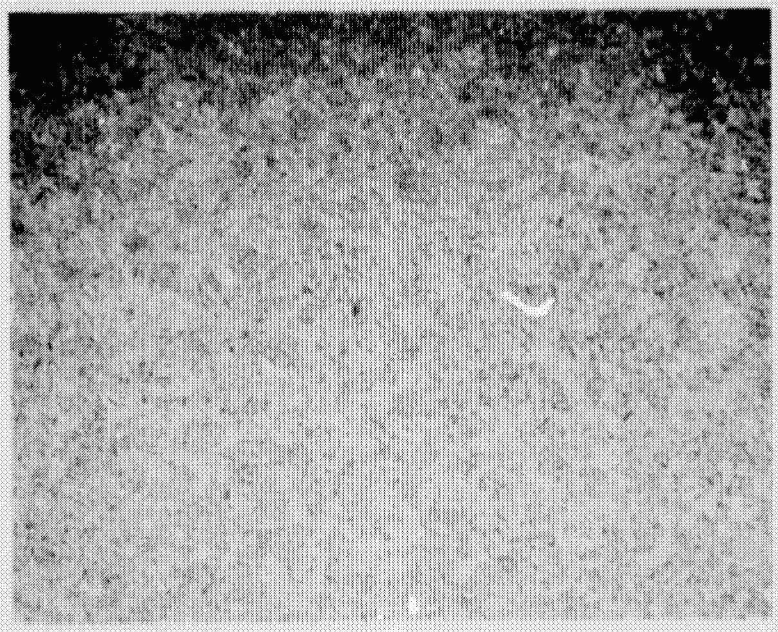


FIGURE 9. B-10 FATIGUE LIFE COMPARISONS OF CBS 600



(a)
Case

Picral Etch (b) 100X
Core

Figure 10. Optical Microstructure of CBS 600, Test Series y.

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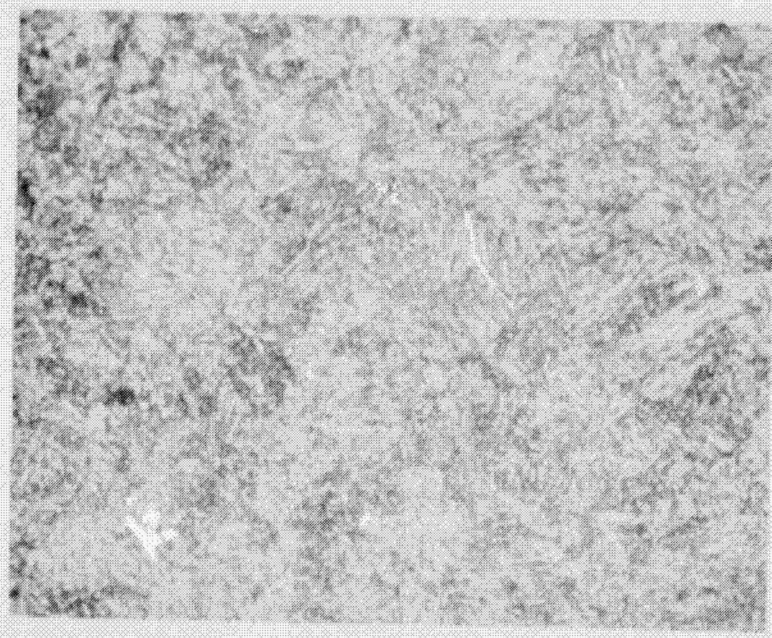
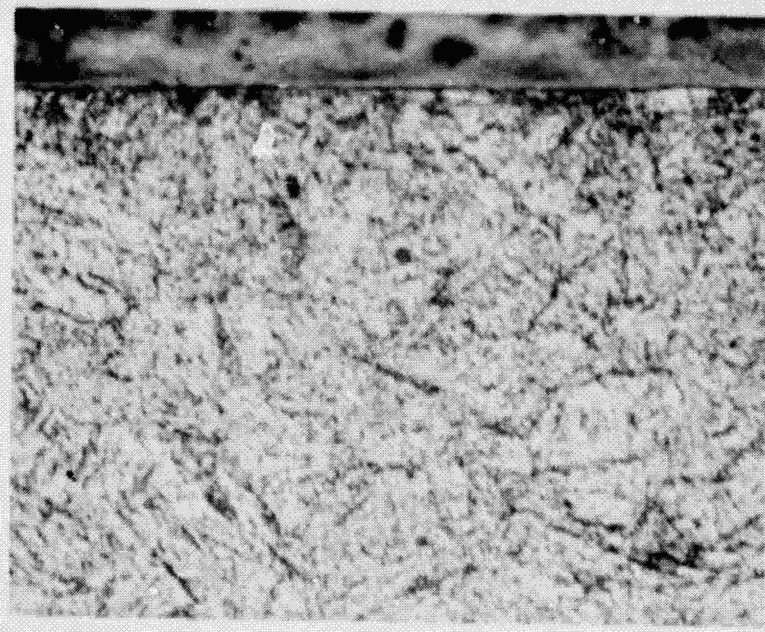
(a)
Case



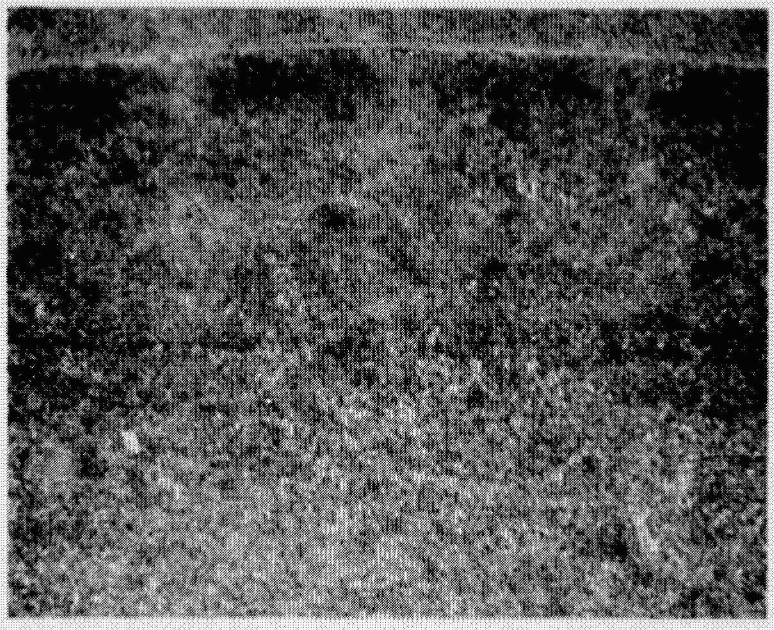
Nital Etch (b) Core 500X

Figure 11. Optical Microstructure of CBS 600, Test Series y.

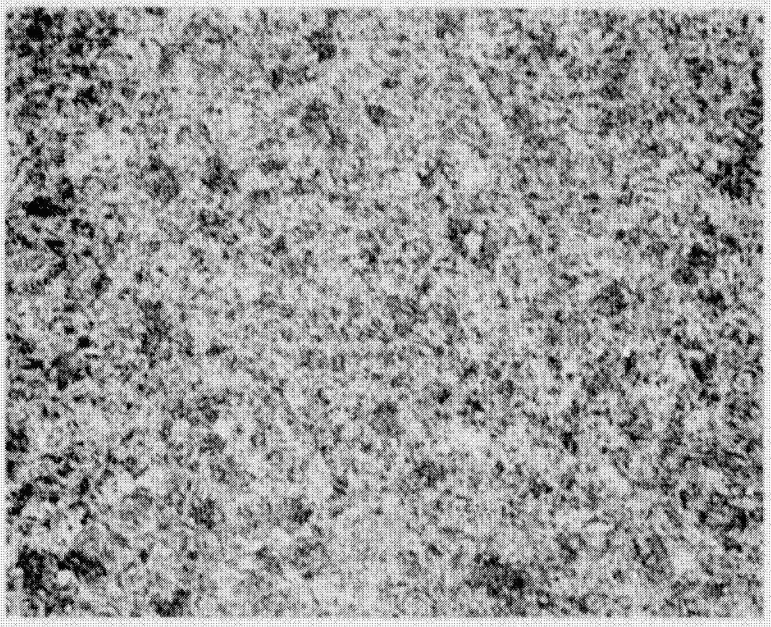


Nital Etch 1000X

Figure 12. Optical Microstructure of CBS 600, Test Series y, Showing Small Carbides Along Prior Austenite Grain Boundaries.



(a)
Case



Picral Etch (b) 100X
Core

Figure 13. Optical Microstructure of CBS 600, Test Series AD.

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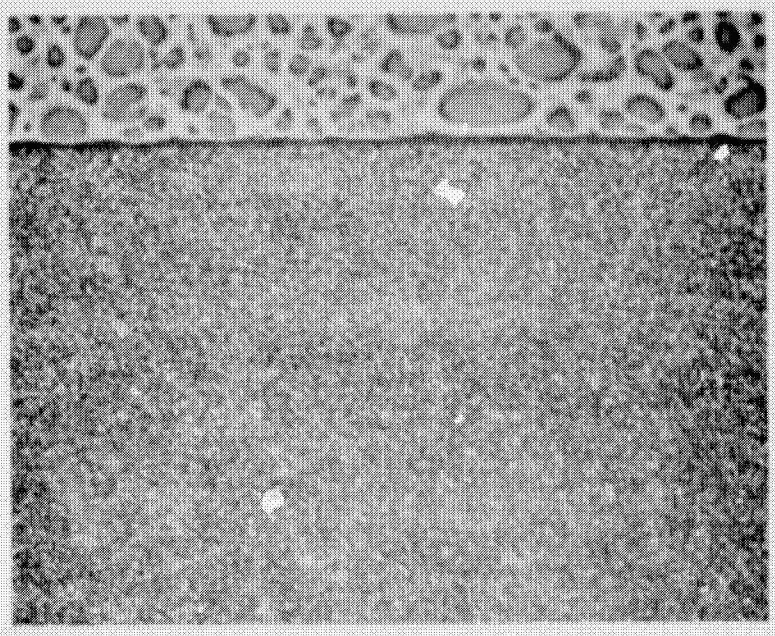
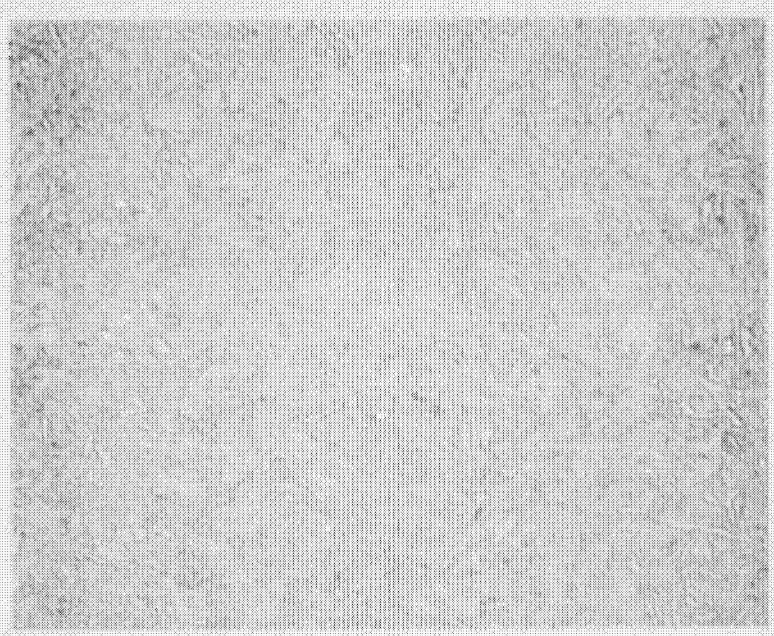


(a)
Case



Nital Etch (b) 500X
Core

Figure 14. Optical Microstructure of CBS 600, Test Series AE.

(a)
Case

Nital Etch (b) 500X
Core

Figure 15. Optical Microstructure of CBS 600, Test Series AF.

No noticeable difference was found in optical microstructure of Test Series AD, AE, and AF, representative microstructure is shown in Figures 13, 14, and 15. The fine carbide network observed in Test Series y was not found in Test Series AD, AE, and AF, indicating carbon potential employed during carburizing cycles was likely to be higher for the case of Test Series y. It should be mentioned here that the microstructure observed in Test Series AD, AE and AF is quite close to the optimum microstructure for bearing and gear applications recommended by the material supplier[11]. CBS 600 is known to have almost 100% martensite in the case, and martensite plus ferrite in the core when heat treated under the recommended procedure. White acicular phases in Figures 14-(b) and 15-(b) are indicated to be ferrite.

A summary of microstructural analysis such as core grain size, case and core hardness, effective case depth and the volume percent of retained austenite present in the case structure is presented in Table 9.

It is apparent from the test results that the rolling contact fatigue life strength of CBS 600 alloy is equivalent to or better than that of VAR AISI 9310 or that of VIM-VAR M-50. It is also found that the effect of different tempering temperatures employed and the introduction of subzero treatment on rolling contact fatigue do not appear to be significant. The reason is attributed to the fact that the variation used was not extensive in this investigation.

Even though specimens from Test Series y have higher retained austenite and are air-melted, no conclusive remarks can be made because the specimens have higher (HRC 65) hardness than other three Test Series AD, AE and AF. However, there is a slight trend toward increased rolling contact fatigue life with increasing retained austenite from 2 to 4%. The trend is statistically insignificant. It appears that further study is needed to find the effect of retained austenite 0 to 10% which is often present in actual applications.

e) <u>CBS 1000M and Vasco X-2</u>

Chemical compositions of CBS 1000M and Vasco X-2 used in this study are provided in Table 10. Both materials are recommended for continuous service up to 600° F (316° C) in bearing and gearing applications. Metallurgically, case structure of CBS 1000M and Vasco X-2 can be said to be comparable. As a matter of fact, Vasco X-2 is a derivative of AISI H-12 tool steel (5 Cr - 1 Mo), being close to AISI H-12 with low carbon content. In CBS 1000M, chromium is reduced to 1% to avoid oxidation problems during carburizing. Three percent nickel is added for toughness and workability. Vanadium is mainly used for gain refinement.

Table 11 describes the details of heat treatment used for CBS 1000M and Vasco X-2. CBS 1000M was triple tempered at approximately 1000° F (538° C) to take advantage of a secondary hardening effect. Vasco X-2 was triple-tempered at 600° F (316° C).

Table 12 summarizes the results of rolling contact fatigue tests of CBS 1000M and Vasco X-2. Weibull presentation of the results are given in Figure

Table 9. Metallurgical Characteristics of CBS 600.

Test Series	Effective* Case Depth,	Case Hardness,	Case Retained Austenite,	Core	
				Hardness HRC	Grain Size (ASTM Number)
y	0.76 (0.030)	65.0	8.7	43.0	7-8
AD	0.84 (0.033)	61.7	4.3	41.0	7-8
AE	0.84 (0.033)	60.3	3.4	41.0	7-8
AF	0.76 (0.030)	61.6	2.1	41.0	7-8

*Depth below the surface at which HRC 58 occurs.

Table 10. Chemical Composition of CBS 1000M and Vasco X-2.

Test Series	Test Materials	Alloying Element, percent by weight (balance Fe)											
		C	Si	Mn	S	P	W	Cr	V	Mo	Co	Ni	Cu
z, AB and AC	VAR CBS 1000M	0.135	0.43	0.48	0.019	0.018	----	1.12	0.33	4.77	----	2.94	0.15
δ	VAR VASCO X-2	0.12	0.88	0.29	0.008	0.012	1.32	4.95	0.42	1.34	0.02	0.06	0.09

Table 11. Heat Treating Process for CBS 1000M & VASCO X-2.

Heat Treating \ Test Materials (Test Series)	VAR CBS 1000M (z)	VAR CBS 1000M (AB)	VAR CBS 1000M (AC)	VAR VASCO X-2 ([illegible])
Preheat	593° C (1100° F) 2 hours	954° C (1750° F) 1 hour, air cooled	968° C (1775° F) 1 hour in vacuum, inert gas quench	1010° C (1850° F) 2-3 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/954° C (1700° F/1750° F)
Reheat	788° C (1450° F) 30 minutes, rapid increase to 1107° C (2025° F)	---	816° C (1500° F)	---
Austenitize	1107° C (2025° F) oil quench	1093° C (2000° F)	1093° F (2000° F) salt quench 552° C (1025° F), air cool	1010° C (1850° F) 1 hour, oil quench
Temper	---	---	371° C (700° F) 1 hour	---
Deep Freeze	-73° C (-100° F) 3 hours	---	-73° C (-100° 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	Temper 316° C (600° F) 2+2+2 hours

Table 12. Summary of RCF Test Results of CBS 1000M and VASCO X-2.

Test Series	Test Materials	B-10 Life, X 10^6 cycles	B-10 Life, X 10^6 cycles	Weibull Slope	Failure[a] Index
Z	VAR CBS 1000M	1.00	1.99	2.73	20/20
AB	VAR CBS 1000M	2.71	6.22	2.27	10/10
AC	VAR CBS 1000M	2.11	4.05	2.89	10/10
δ	VAR Vasco X-2	6.31	15.13	2.16	20/20

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

Test Conditions:

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

16 where the data for VIM-VAR AISI M-50 and VAR AISI 9310 are included for comparison. B-10 lives of CBS 1000M, Vasco X-2 and baseline data of the VIM-VAR AISI M-50 and VAR AISI 9310 are compared in a bar chart in Figure 17.

It is shown within the range of the present experimental conditions that VAR CBS 1000M is inferior to both VIM-VAR AISI M-50 and VAR AISI 9310 while Vasco X-2 is better than the baseline materials. Direct comparison between Vasco X-2 and CBS 1000M, however, appears to be invalid because of their differences in the amount of retained austenite present in the case structure. The superior performance of Vasco X-2 is attributed to the excessive amount of retained austenite (22%) (Table 13). It is noted that if these materials are used for rolling element bearings, such high retained austenite may not be desirable.

A summary of metallurgical analyses on CBS 1000M and Vasco X-2 is given in Table 13. Optical microstructures of these materials are shown in Figure 18 through 22. It is interesting to note that a microstructural transformation was observed in CBS 1000M due to rolling contact fatigue. This is clearly shown in Figure 21. The microstructural change was observed at about 0.18 mm (0.007 in.) below the surface. It is consistent with the distance from the surface where maximum shear stress exists in the specimen. No microstructural changes were observed in all the other alloys used in the present investigation. The reason for this is unknown. The evidence for high retained austenite found in Vasco X-2 is shown in Figure 22-(a).

d) Nitriding Alloys

The chemical compositions of nitriding alloys, VIM-VAR Super Nitralloy, AM Nitralloy 135 and VAR Nitralloy N are described in Table 14. Table 15 illustrates the heat treating details used for the alloys. An additional tempering at 593° C (1100° F) for four hours was given to heating treating of VIM-VAR Super Nitralloy. This temper reduces core hardness from HRC 50 to HRC 42. The results of rolling contact fatigue tests on nitriding alloys are summarized in Table 16. Figure 23 shows the corresponding results plotted graphically on the Weibull coordinates. B-10 lives are compared as a bar chart in Figure 24. Included in Figures 23 and 24 are the test results on VIM-VAR AISI M-50 and VAR AISI 9310.

It is apparent from the above results that the rolling fatigue life of these nitriding alloys, VIM-VAR Super Nitralloy, AM Nitralloy 135 and VAR Nitralloy N is inferior to VIM-VAR AISI M-50 and to VAR AISI 9310.

Figures 25, 26, and 27 are optical micrographs showing case and core microstructures of VIM-VAR Super Nitralloy, AM Nitralloy 135 and VAR Nitralloy N, respectively. Delineated formation of nitrides, along grain boundaries, are evident in nitrided case structures of the alloys investigated. The preferential formation of nitrides is, in general, a common phenomenon in nitriding alloys.

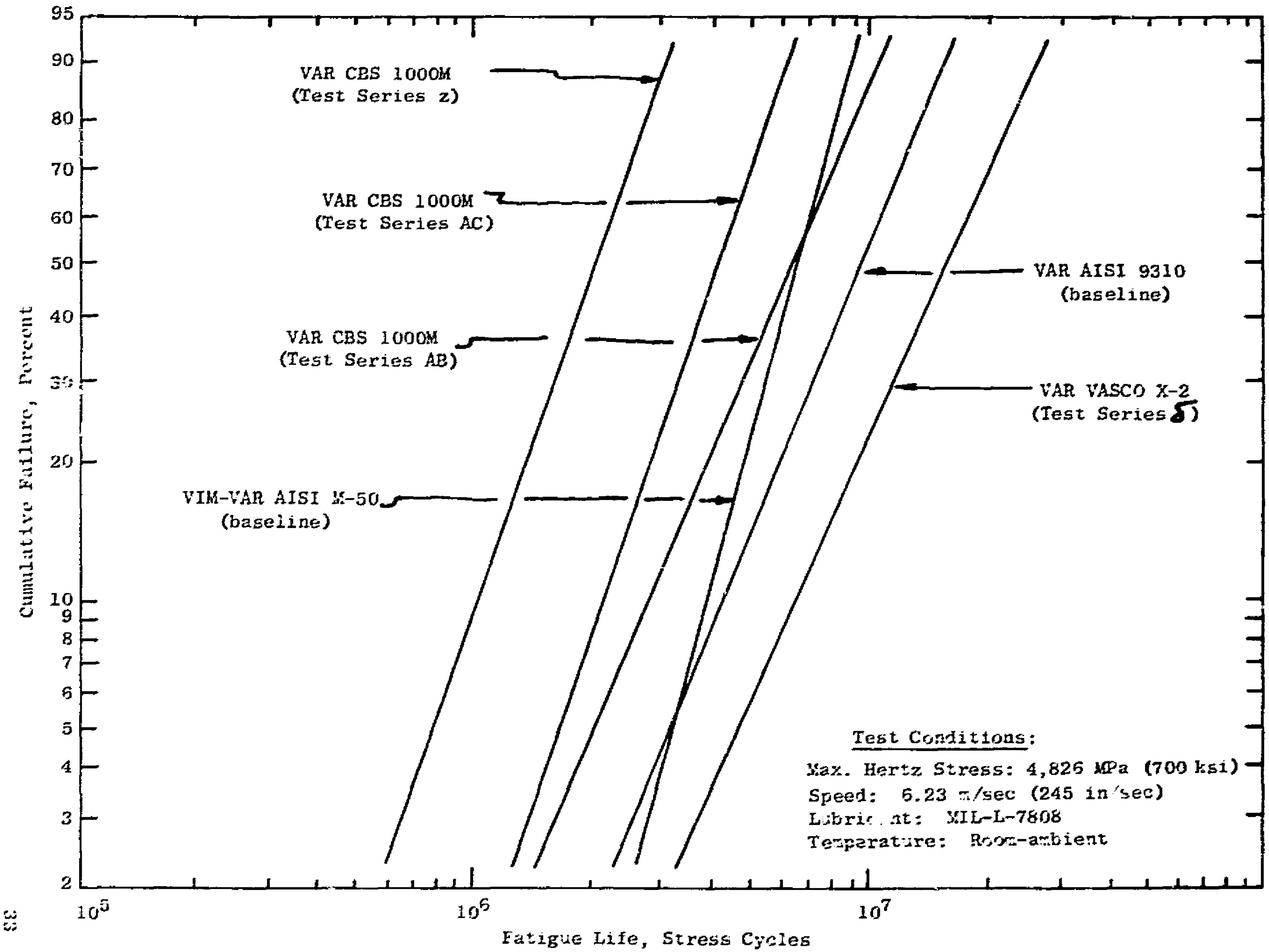


FIGURE 16. Fatigue Life Comparison of CBS 1000M and Vasco X-2

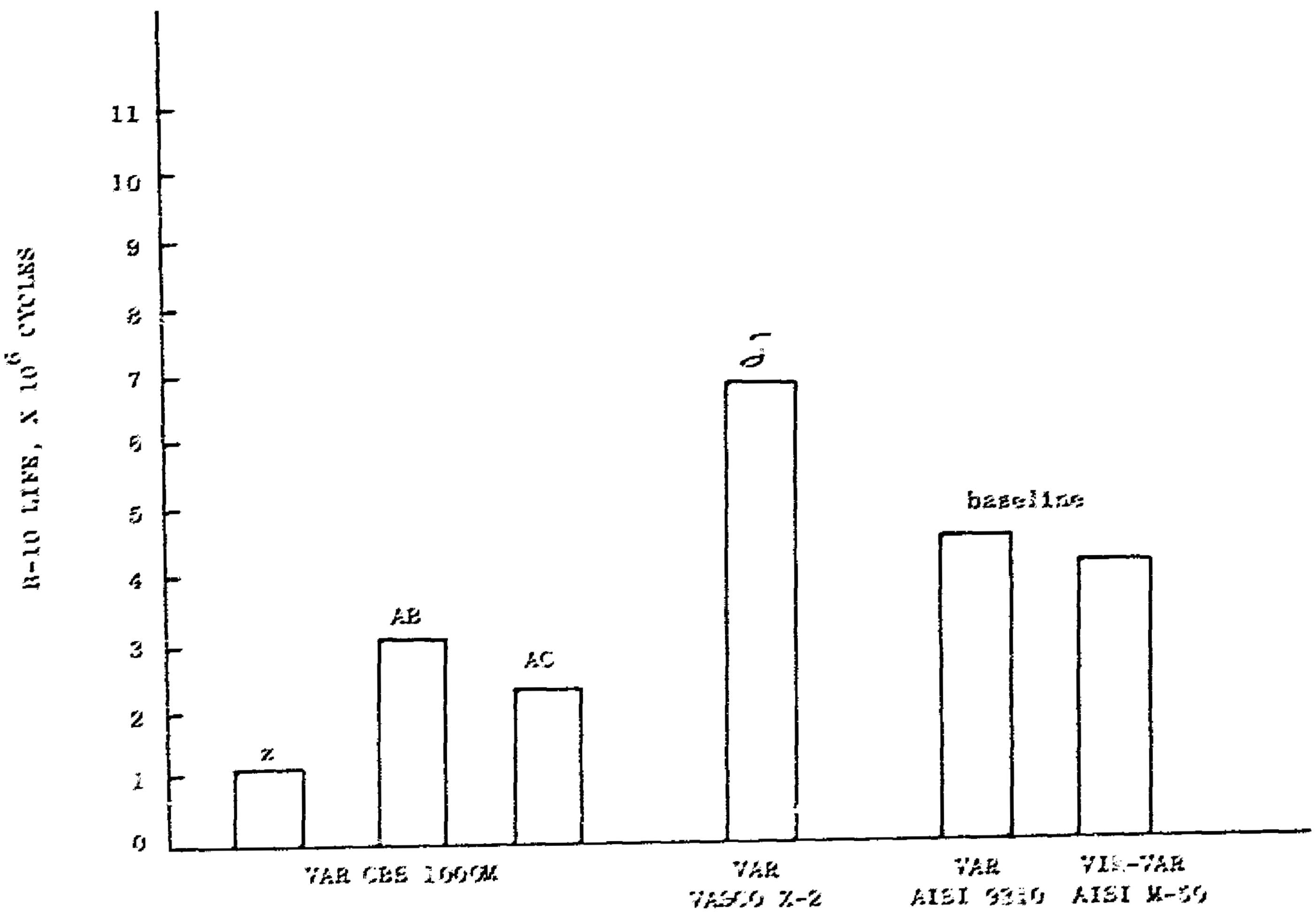
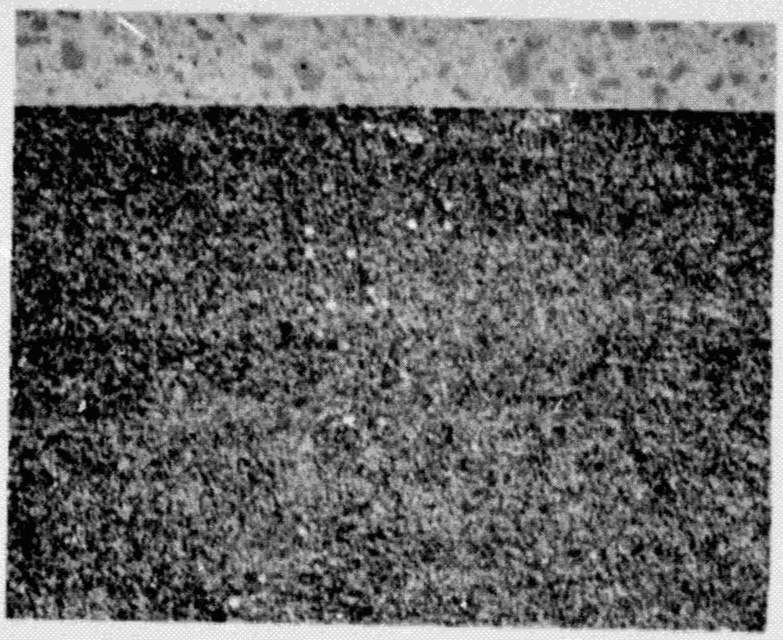


FIGURE 17. B-10 FATIGUE LIFE COMPARISON OF CBS 1000M AND VASCO X-2

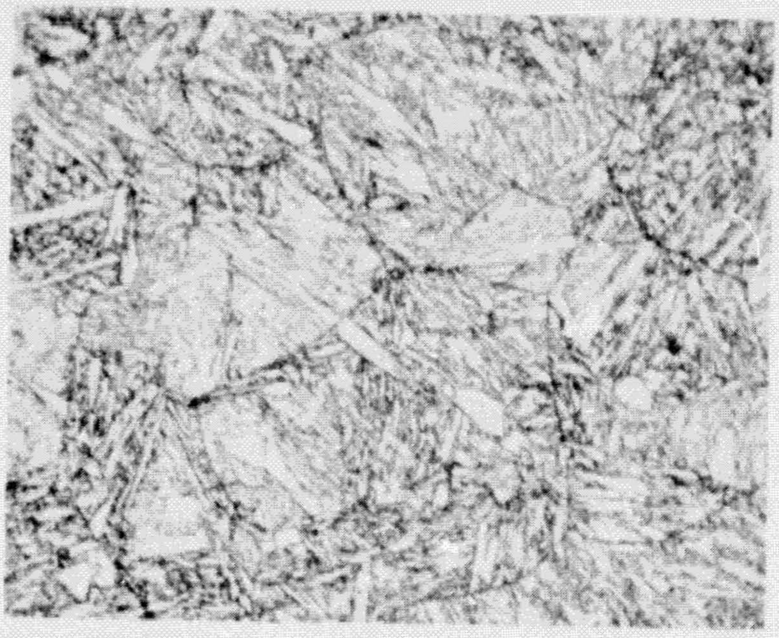
Table 13. Metallurgical Characteristics of CBS 1000M and Vasco X-2.

Test Series	Test Materials	Effective Case Depth, mm (in)	Case Hardness, HRC	Core Hardness, HRC	Retained Austenite, %
Z	VAR CBS 1000M	0.75 (0.030)	60.1	45.0	N.D.
AB	VAR CBS 1000M	1.09 (0.043)	61.6	47.0	1.7
AC	VAR CBS 1000M	0.76 (0.030)	60.9	47.0	0.4
δ	VAR Vasco X-2	0.89 (0.035)	60.0	43.0	22.0

N.D.: Not-Detected

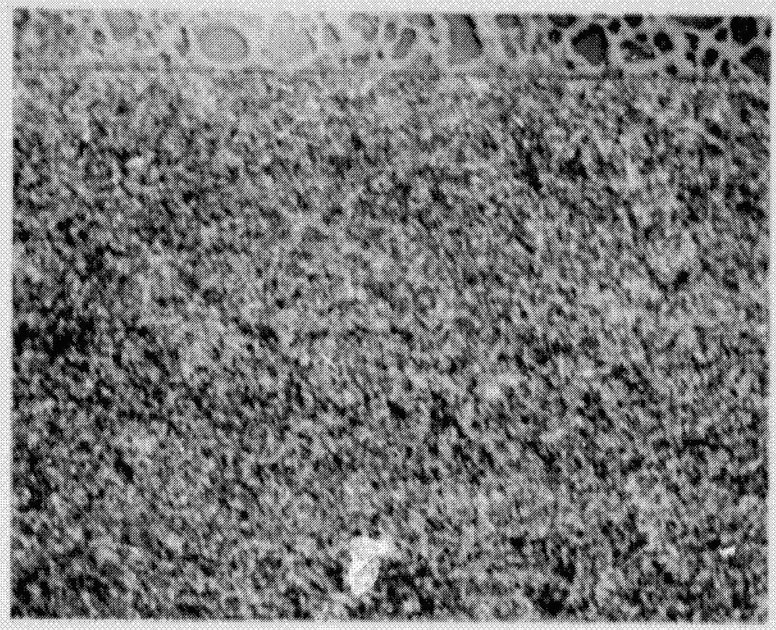


(a)
Case



Nital Etch (b) 500X
Core

Figure 18. Optical Microstructure of CBS 1000M, Test Series z.



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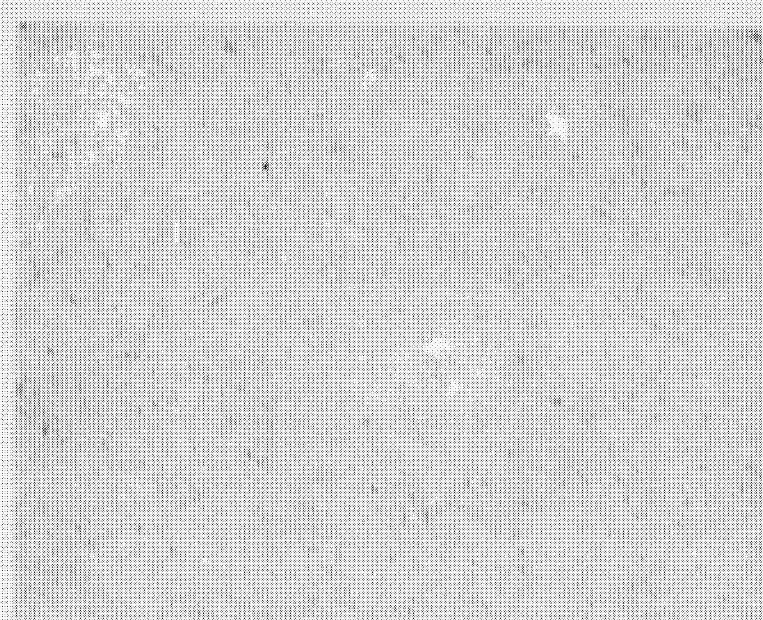
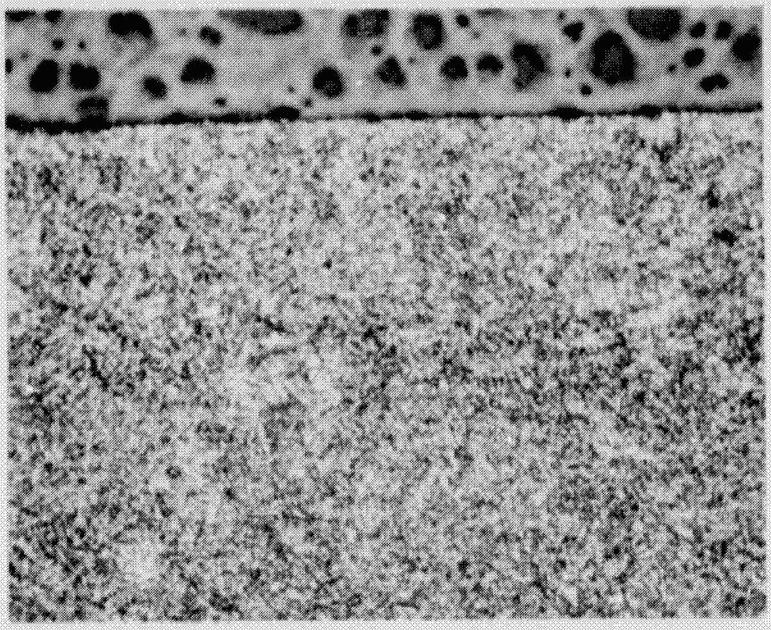
(a)
Case



Nital Etch (b) 500X
Core

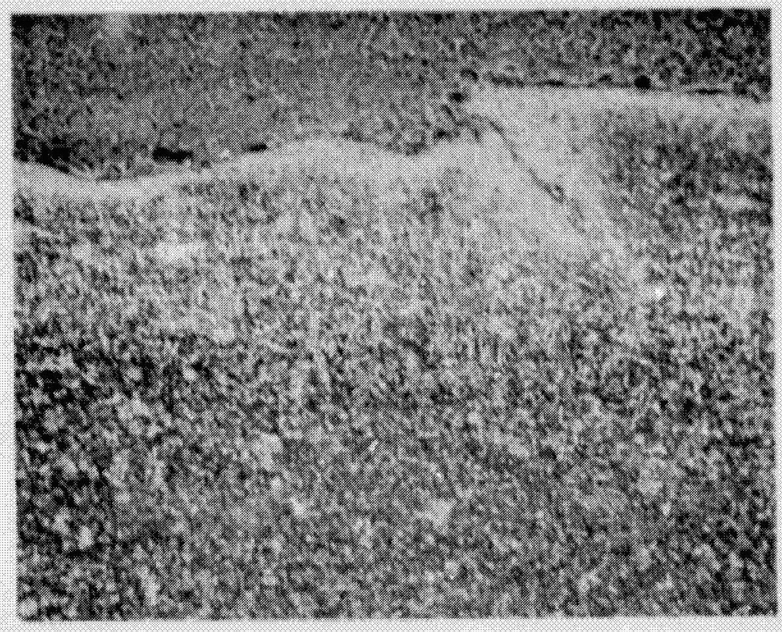
Figure 19. Optical Microstructure of CBS 1000M, Test Series AB.



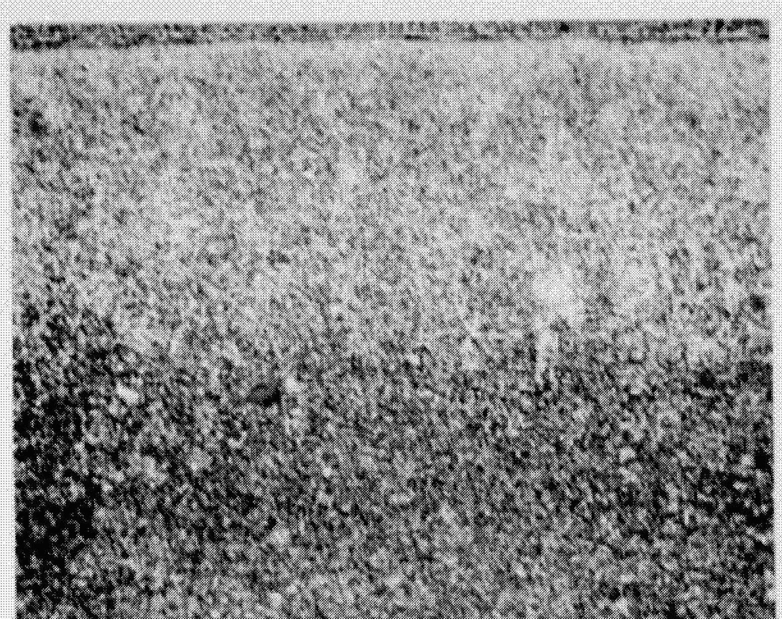
(a)
Case

Nital Etch (b) 500X
Core

Figure 20. Optical Microstructure of CBS 1000M, Test Series AC.



(a)
Case

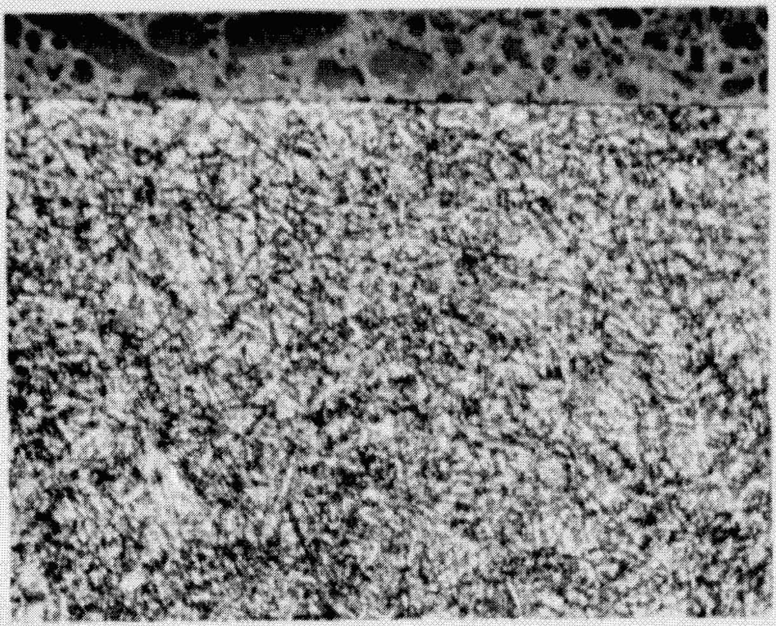


Nital Etch (b) 200X
Core

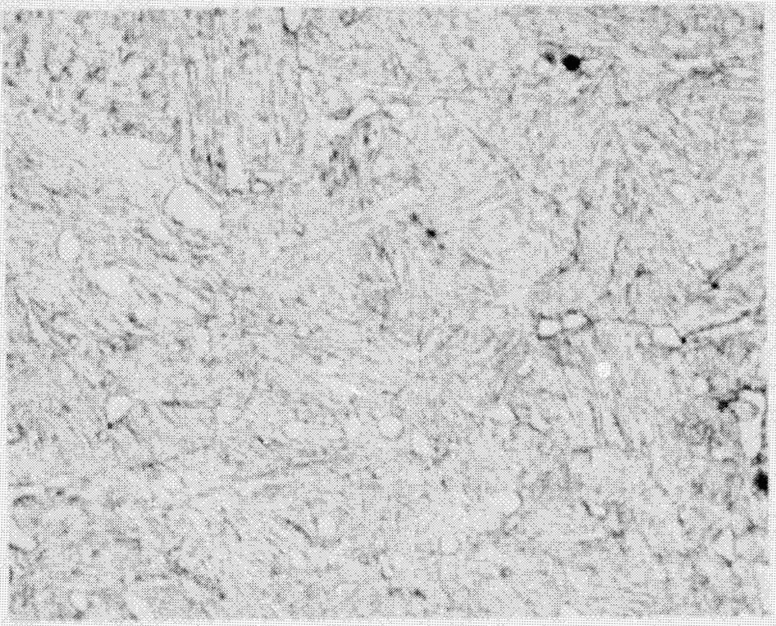
Figure 21. Optical Micrographs Showing Fatigue Spalling and Structural Change in CBS 1000M (Test Series AC) After 6.14×10^6 Cycles of RCF Testing.

Nital Etch (c) 500X

Figure 21. Optical Micrographs Showing Fatigue Spalling and Structural Change in CBS 1000M (Test Series AC) After 6.14×10^6 Cycles of RCF Testing (Concluded).



(a)
Case



Nital Etch (b) 500X
Core

Figure 22. Optical Microstructure of Vasco X-2, Test Series 8.

Table 14. Chemical Composition of Nitriding Alloys.

Test Series	Test Material	Alloying Element, percent by weight (Balance Fe)									
		C	Si	Mn	S	P	Cr	Mo	Ni	Al	Cu
u	VIM-VAR Super Nitralloy	0.24	0.22	0.25	0.003	0.005	0.58	0.26	5.16	2.06	---
v	AM Nitralloy 135	0.41	0.34	0.63	0.012	0.010	1.63	0.39	0.21	1.04	---
ε	VAR Nitralloy N	0.25	0.24	0.58	0.003	0.004	1.18	0.27	3.54	1.22	0.06

Table 15. Heat Treating Process for Nitriding Alloys.

Heat Treating \ Test Materials (Test Series)	VIM-VAR Super Nitralloy (u)	AM Nitralloy 135 (v)	VAR Nitralloy N (ε)
Preheat	927° C (1700° F) 15 minutes, AC to RT	---	---
Austenitize	899° C (1650° F) oil quench	927° C (1700° F) oil quench	899° C (1650° F) oil quench
Temper	566° C (1050° F) 8 hours	649° C (1200° F) 1 hour	649° C (1200° F) 1 hour
Nitride	527° C (980° F) 72+72 hours	527° C (980° F) 72+72 hours	527° C (980° F) 72+72 hours
Temper	593° C (1100° F) 4 hours	---	---

Table 16. Summary of RCF Test Results of Nitriding Alloys.

Test Series	Test Materials (Melting Process)	B-10 Life, x 10^6 cycles	B-50 Life, x 10^6 cycles	Weibull Slope	Failure[a] Index
u	Super Nitralloy (VIM-VAR)	2.44	4.69	2.89	20/20
v	Nitralloy 135 (Air Melted)	1.43	4.37	1.68	30/30
r	Nitralloy N (CVM)	2.30	4.91	2.48	20/20

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

Test Conditions:

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

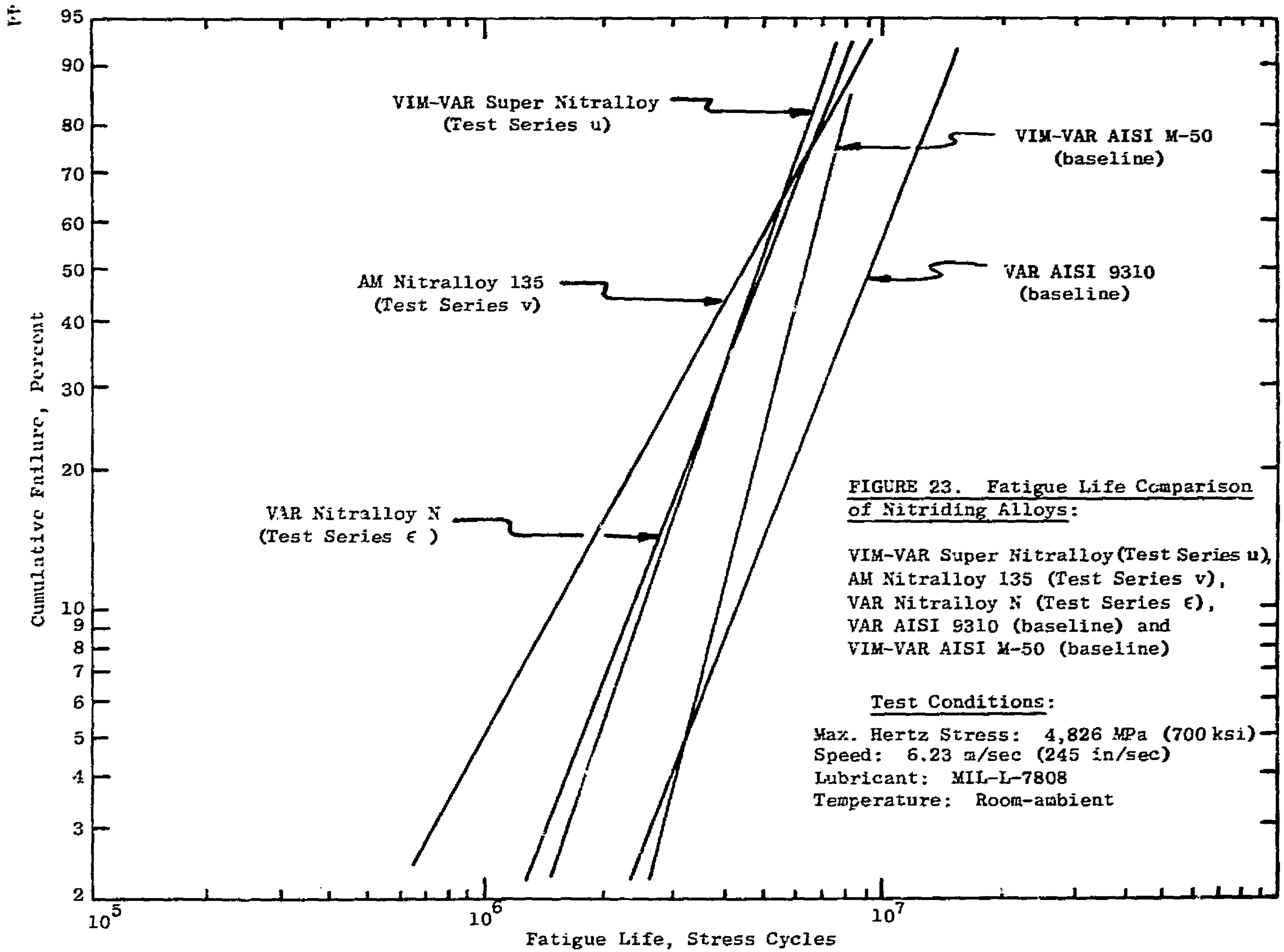


Figure 23. Fatigue Life Comparison of Nitriding Alloys

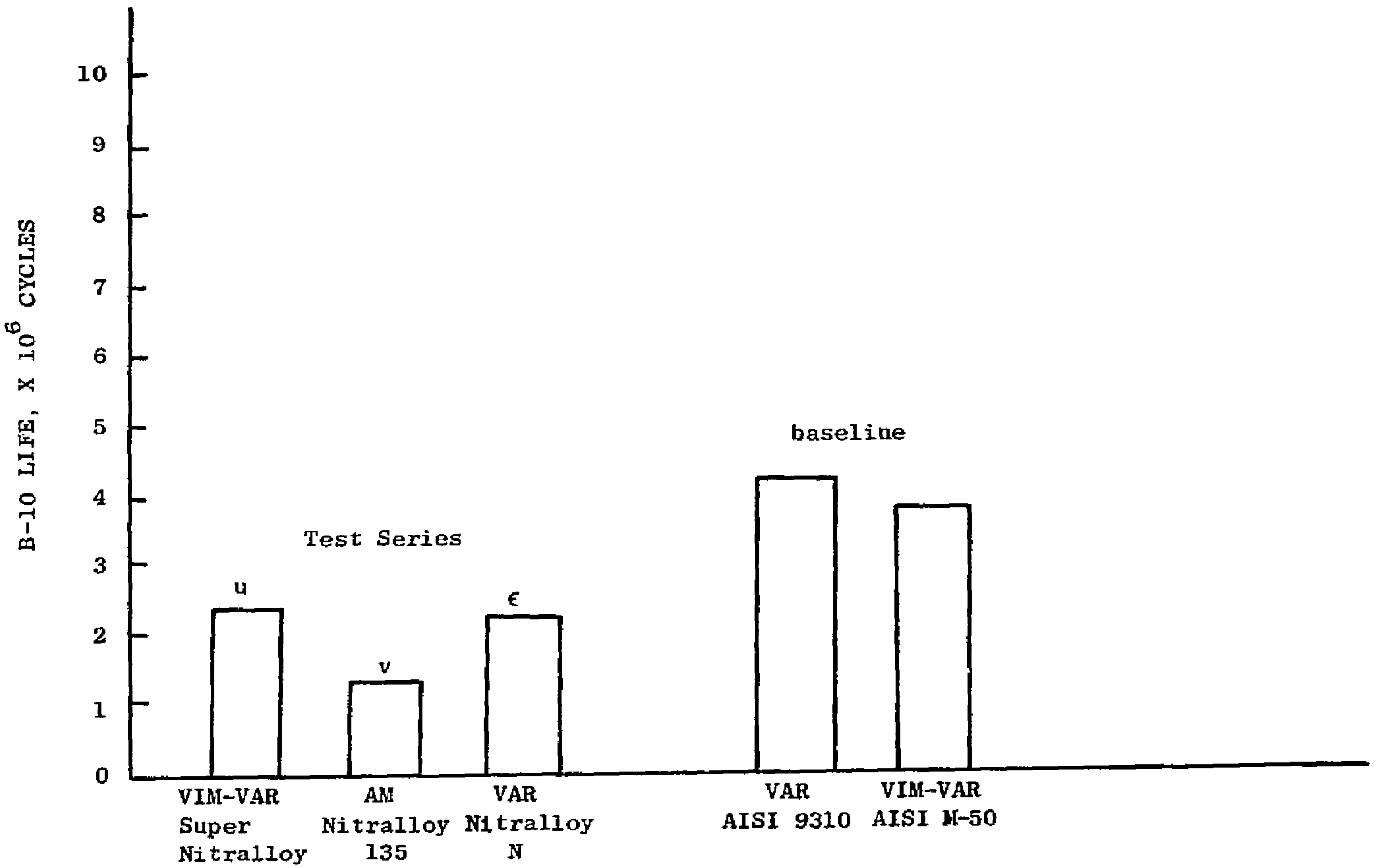
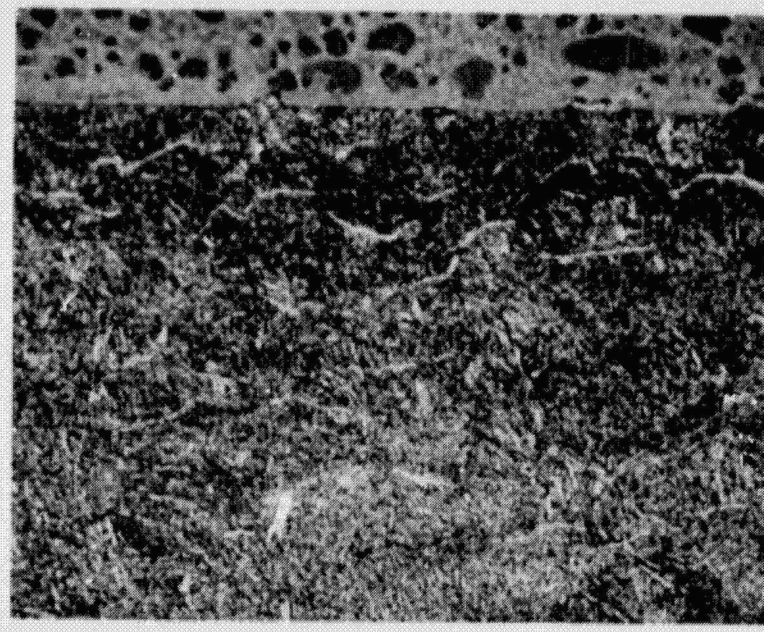


FIGURE 24. B-10 FATIGUE LIFE COMPARISON OF NITRIDING ALLOYS

(a)
Case

Nital Etch (b) 500X
Core

Figure 25. Optical Microstructure of Super Nitralloy, Test Series 4.



(a)
Case

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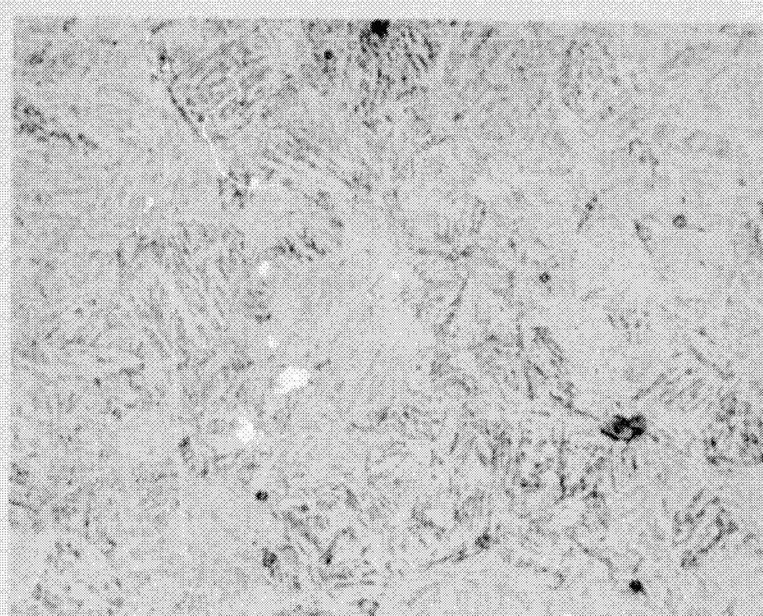
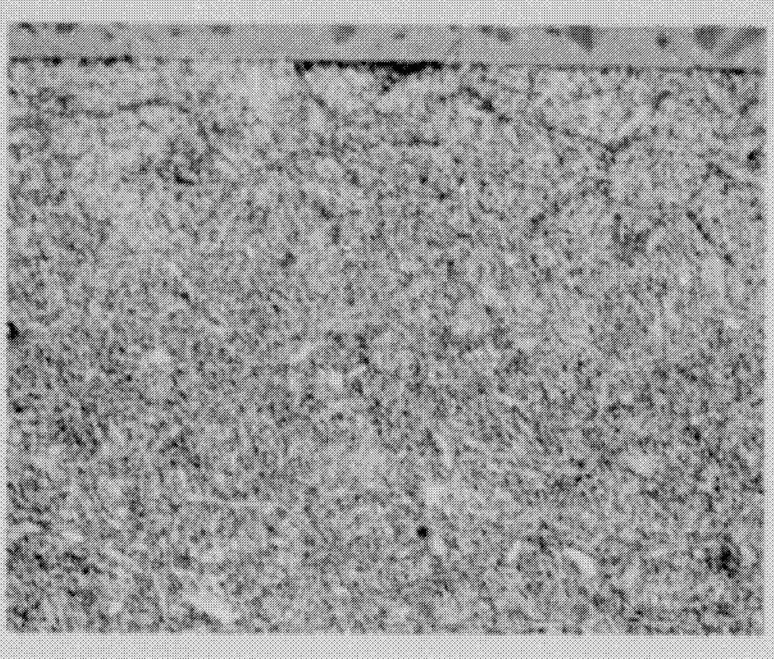


Nital Etch (b) 500X
Core

Figure 26. Optical Microstructure of Nitralloy 135, Test Series V.



(a)
Case

Nital Etch (b) 500X
Core

Figure 27. Optical Microstructure of Nitralloy N, Test Series c.

Table 17 is an outline of metallurgical characteristics of nitriding alloys. Effective case depths were measured to be 0.40 mm (0.015 inch) after 144 hours (72 + 72) nitriding at 527° C (980° F). 4.8 volume percent of retained austenite was present in the case surface of Super Nitralloy. Retained austenite was not detected in both Nitralloy 135 and Super Nitralloy.

The shallow case depths and/or the preferential segregation of nitrides on grain boundaries perpendicular to diffusion direction could contribute to the poor rolling contact fatigue performance of nitriding alloys.

It has been found that a nitrided case can be renitrided at higher (i.e., 85%) dissociation of ammonia (NH_3). The renitriding cycle increases the case depth and also seems to eliminate the envelopment of grain boundaries with nitrides(12). Disadvantages of nitriding are: (1) the excessive nitriding time (100 + hours) and (2) the formation of white layer phases. A more recent process known as ion-nitriding is said to overcome these problems(13). Ion-nitrided materials show improved fatigue strength and the white layer control is easier. Since ion-nitriding uses less energy and nitriding time with advantages in mechanical wear properties, the process appears to be attractive.

e) Through-Hardening Alloys

Four through-hardening alloys, VAR Vasco Matrix II, VAR AISI W-1, AISI O-2 and AISI S-2 were investigated. Table 18 gives the chemical composition of the alloys. AISI W-1, AISI O-2 and AISI S-2 are low alloy steels. Vasco Matrix II has a high alloy content with 0.55% carbon plus nearly 20% alloying elements. Its metallurgical characteristics are similar to AISI M-50, AISI T-1 and other high speed tool steels. Heat treating processes for the through-hardening alloys are described in Table 19. As shown in Table 19, AISI W-1, AISI O-2 and AISI S-2 were temperated at low temperature because of lean alloying elements.

Table 20 is a summary of the results from rolling contact fatigue tests on through-hardening alloys. The results are also plotted in the Weibull function as shown in Figure 28. As previously, the results of VIM-VAR AISI M-50 and from VAR AISI 9310 are included in Figure 28 for comparison. B-10 lives of these are given as a histogram in Figure 29.

The above results indicate that VAR AISI W-1 and VAR AISI O-2 are superior to VAR Vasco Matrix II, and is equivalent to VIM-VAR AISI M-50 and VAR AISI 9310, and VAR AISI S-2 is also indicated to be inferior to VIM-VAR AISI M-50 and VAR AISI 9310 in rolling contact fatigue life performance.

Moderate size carbide particles and fine grains observed in Vasco Martix II are shown in an optical micrograph (Figure 30). Optical microstructures of AISI W-1, AISI O-2, and AISI S-2 are shown in Figures 31, 32, and 33 respectively. A relatively high density of inclusions was found in AISI S-2. Poor rolling contact fatigue test results of AISI S-2 may be mainly due to the inclusions found in the microstructure. Hardness and the amount of retained austenite are described in Table 21. Relatively high amount of retained austenite, 6.6% and 9.6% respectively, was found in AISI W-1 and AISI O-2. This may account for the longer lives observed in these alloy than

Table 17. Metallurgical Characteristics of Nitriding Alloys.

Test Series	Test Materials (Melting Process)	Effective Case Depth mm (in.)	Case Hardness, HRC	Core Hardness, HRC	Retained Austenite, %
4	Super Nitralloy (VIM-VAR)	0.43 (0.017)	60.4	42.0	4.8
7	Nitralloy 135 (Air Melted)	0.38 (0.015)	60.6	35.0	N.D.*
8	Nitralloy N (VIM)	0.38 (0.015)	62.9	46.0	N.D.

*N.D.: Not Detected.

Table 18. Chemical Composition of Through-Hardening Alloys.

Test Series	Test Materials	Alloying Element, Percent by Weight (Balance Fe)									
		C	Si	Mn	S	P	W	Cr	V	Mo	Co
ω	VAR Vasco Matrix II	0.57	0.22	0.026	0.021	0.008	1.02	3.86	1.0	5.07	7.82
α	VAR AISI W-1	1.07	0.27	0.35	0.003	0.003	—	—	—	—	—
β	VAR AISI O-2	0.93	0.29	1.43	0.003	0.005	—	—	—	—	—
γ	VAR AISI S-2	0.48	1.02	0.46	0.003	0.005	—	—	0.01	—	—

Table 19. Heat Treating Process for Through-Hardening Alloys.

Heat Treating \ Test Materials (Test Series)	VAR Vasco Matrix II (ω)	VAR AISI W-1 (α)	VAR AISI O-2 (β)	VAR AISI S-2 (γ)
Preheat	899° C (1650° F) 30 minutes, AC to RT	482° C (900° F)	482° C (900° F)	482° C (900° F)
Austenitize	1104° C (2020° F) quench in salt, 538° C (1000° F) AC to RT	788° C (1450° F) brine quench	816° C (1500° F) oil quench	899° C (1650° F) brine quench
Temper	510° C (950° F) 2+2 hours	191° C (375° F) 1 hour	177° C (350° F) 1 hour	66° C (150° F) 1 hour

Table 20. RCF Test Results of Through-Hardening Alloys.

Test Series	Test Materials	B-10 Life, x 10^6 cycles	B-50 Life, x 10^6 cycles	Weibull Slope	Failure[(a)] Index
W	VAR Vasco Matrix II	3.60	8.01	2.35	20/20
α	VAR AISI W-1	5.95	19.68	1.58	17/20
β	VAR AISI O-2	5.10	18.70	1.45	14/20
γ	VAR AISI S-2	1.23	5.41	1.27	20/20

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

Test Conditions:

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

Table 21. Metallurgical Characteristics of Through-Hardening Alloys.

Test Series	Test Materials	Hardness HRC	Retained Austenite, %
W	VAR Vasco Matrix II	62.6	1.2
α	VAR AISI W-1	61.2	6.6
β	VAR AISI O-2	62.3	9.6
γ	VAR AISI S-2	60.4	1.2

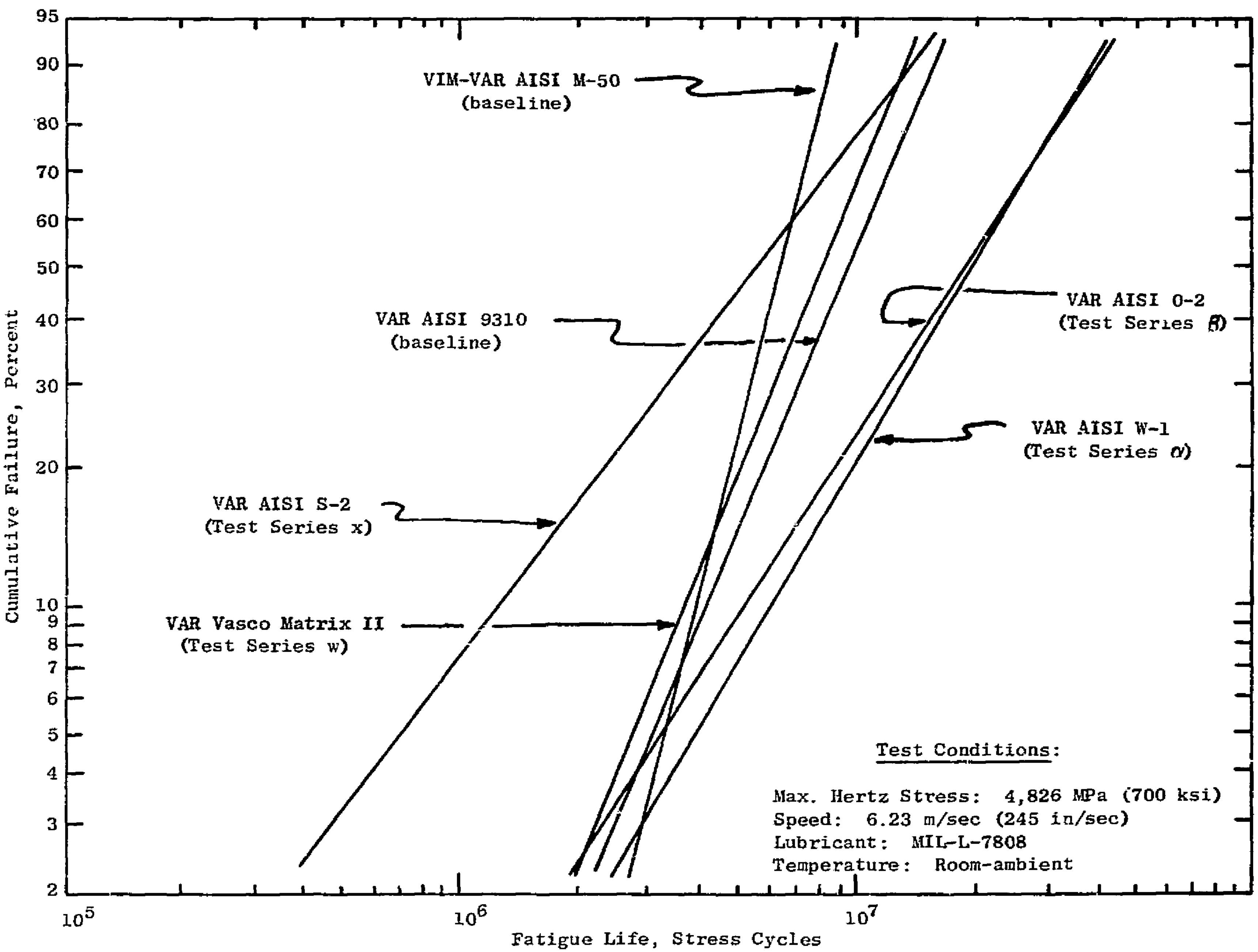


FIGURE 28. Fatigue Life Comparison of Through-Hardening Alloys

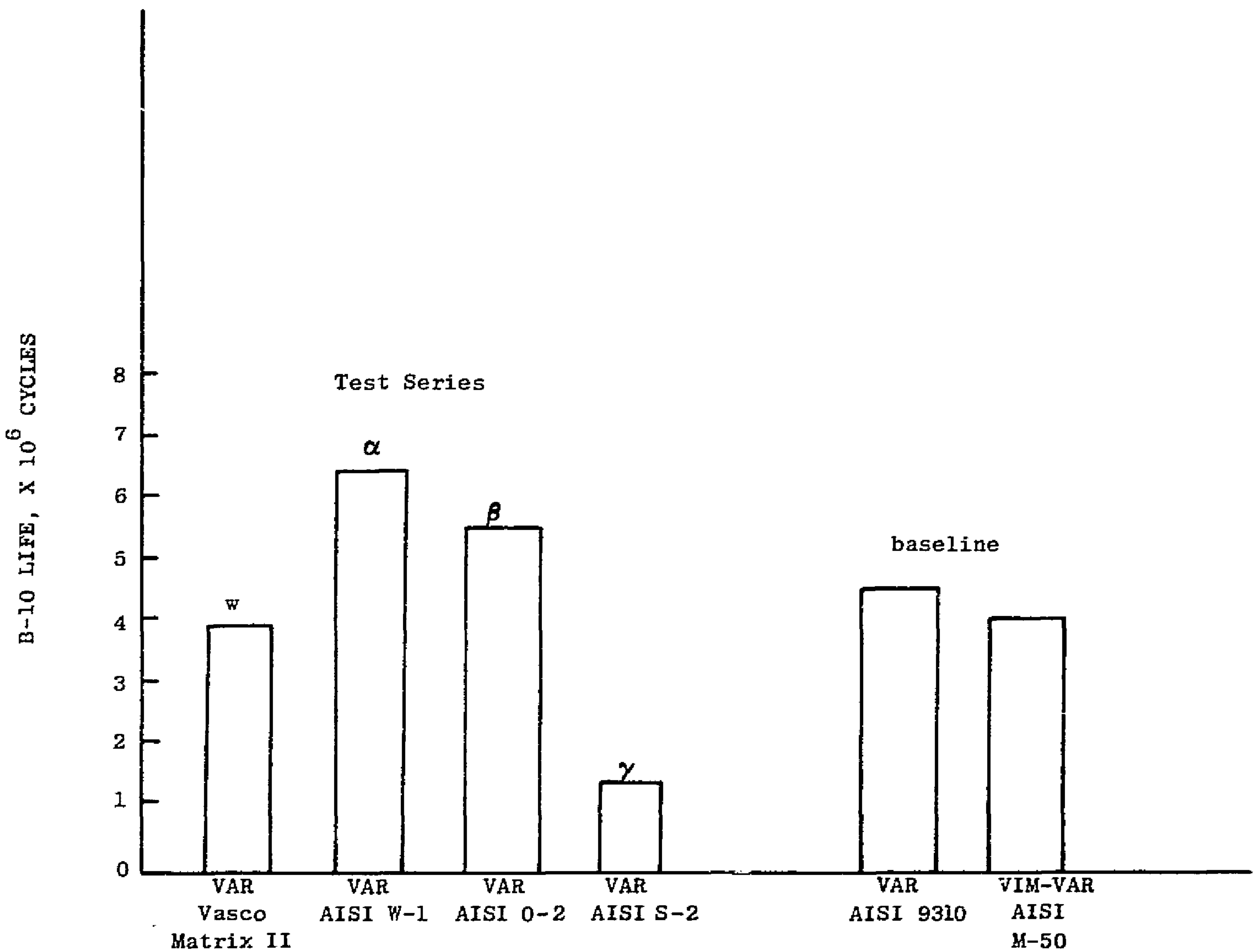
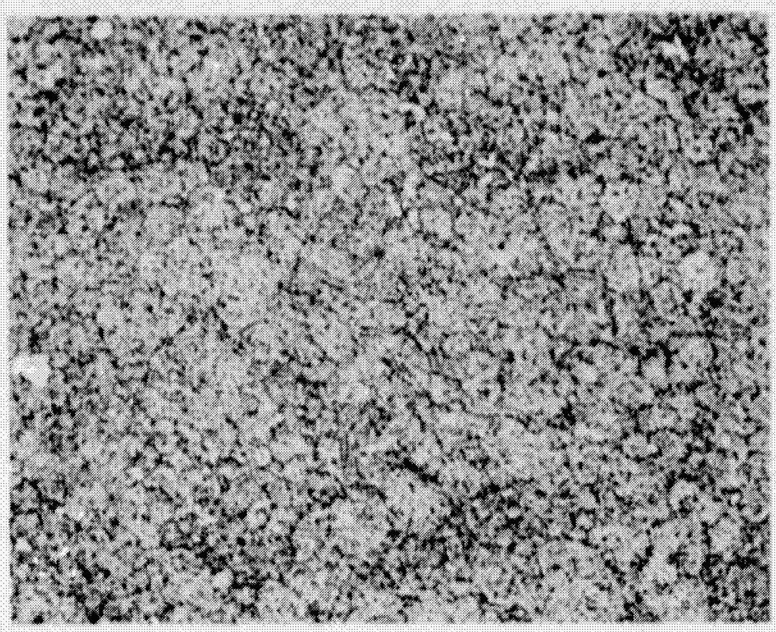
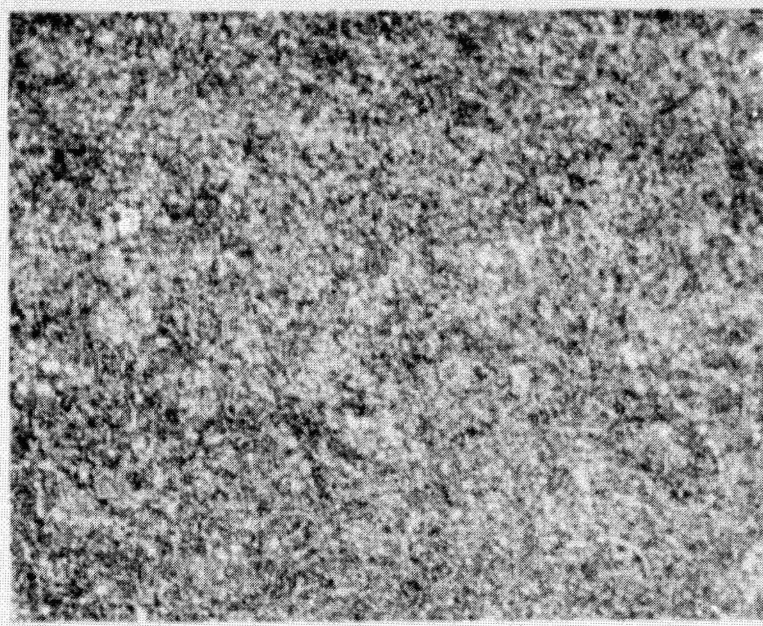


FIGURE 29. B-10 FATIGUE LIFE COMPARISON OF THROUGH-HARDENING ALLOYS



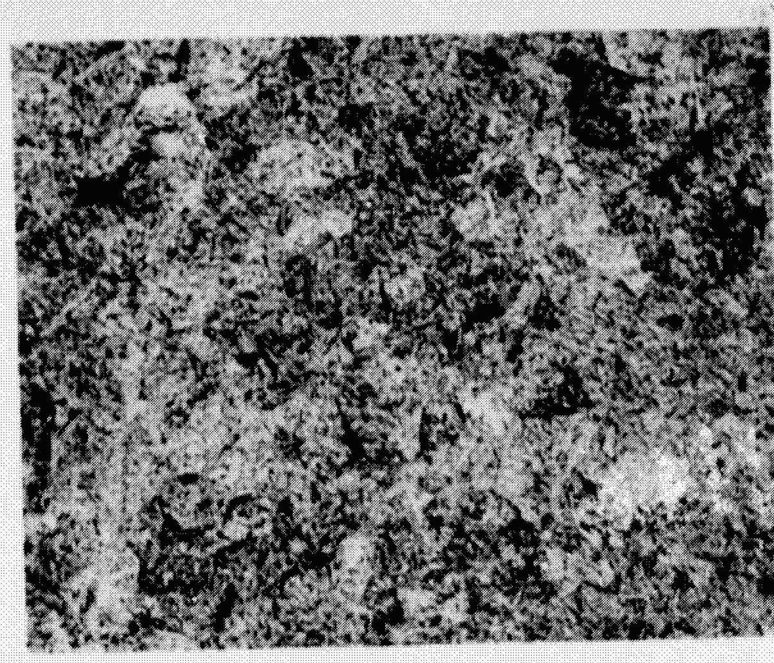
Nital Etch 500X

Figure 30. Optical Microstructure of Vasco Matrix II, Test Series w.



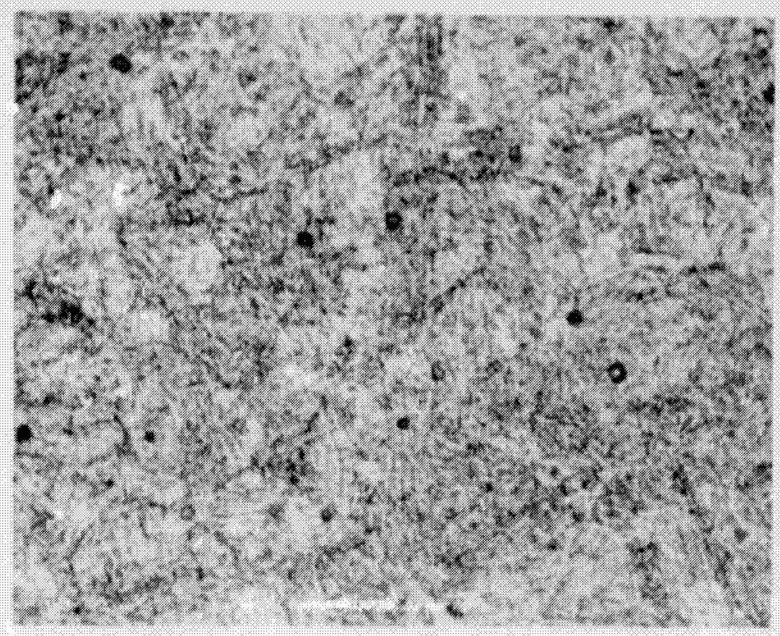
Nital Etch 500X

Figure 31. Optical Microstructure of AIAI W-1, Test Series α.



Nital Etch 500X

Figure 32. Optical Microstructure of AISI O-2, Test Series B.



Nital Etch 500X

Figure 33. Optical Microstructure of AISI S-2, Test Series γ.

VIM-VAR AISI M-50. As mentioned previously, these high percentage of retained austenite may not be desirable for rolling element bearings.

IV. SUMMARY AND CONCLUSIONS

Rolling element fatigue lives were evaluated with eleven alloys in the General Electric Rolling Contract (RC) rigs. Several different heat treatments and/or melting processes have been studied with three carburizing alloys. Metallurgical analyses were made before and after the RC rig tests. Test data was statistically analyzed using the Weibull distribution function. The results were compared with the standard aviation alloys, VIM-VAR AISI M-50 and VAR AISI 9310. The following conclusions were obtained.

For AISI 9310

- Rolling contact fatigue life of VAR AISI 9310 is equivalent to or slightly better than VIM-VAR M-50.
- It was found that double vacuum process did not improve rolling contact fatigue life over single vacuum process in AISI 9310.
- It was also found that rolling contact fatigue life is dependent on level of retained austenite present in the case structure. In the range of 10 to 20 volume percent retained austenite in the case, B-10 life of AISI 9310 was shown to be increased more than three times, from 4.18×10^6 cycles to 14.82×10^6 cycles. Little change in rolling contact fatigue life was observed between specimens with 8.3 and 11.2 percent retained austenite.

For CBS 600

- Rolling contact fatigue life performance of CBS 600 was found to be equivalent to or better than that of VAR AISI 9310 and VIM-VAR AISI M-50.
- The effects of different tempering temperatures employed and the introduction of freezing cycles on rolling contact fatigue do not appear to be significant. The reason is attributed to the fact that the variation employed was not extensive in this investigation.

For CBS 1000M and Vasco X-2

- VAR CBS 1000M is inferior to VIM-VAR AISI M-50 and VAR AIS 9310, while VAR Vasco X-2 is superior to the two base materials. The superior performance of Vasco X-2 is attributed to the excessive retained austenite present in the case microstructure.

For Nitriding Alloys

- Rolling contact fatigue life performance of nitriding alloys, VIM-VAR Super Nitralloy, AM Nitralloy 135 and VAR Nitralloy N is inferior to VIM-VAR AISI M50 and to VAR AISI 9310.

For Through-Hardening Alloys

- VAR AISI W-1 and VAR AISI 0-2 are superior to VIM-VAR AISI M-50 and VAR AISI 9310 in rolling contact fatigue performance.
- VAR Vasco Matrix II is found to be equivalent to VIM-VAR AISI M-50.
- The rolling contact fatigue life behavior of VAR AISI S-2 is found to be inferior to that of VIM-VAR AISI M-50. This may be due to the high degree of the inclusions observed.

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VI. APPENDICES

Appendix A

Table 22. Physical Properties of Lubricant, Stauffer Jet I. (MIL-L-7808G)

		Source
Kinematic Viscosity, cs		
-20° F	480.0	(2)
100	14.76	(1)
210	3.70	(1)
400	1.2	(2)
Fire Point, ° F	490	(3)
Flash Point, ° F	425	(1)
Pour Point, ° F	Below -75	(1)
Specific Gravity, 60/60° F	0.950	(3)
Vapor Pressure, mm Hg		
100° F	ca. 10^{-5}	(4)
35[illegible]° F	0.88	(4)
400° F	1.45	(4)
Specific Heat, Btu/lb-° F		
100° F	0.470	(2)

(1) Batch 3979
(2) Vendor Data, Extrapolated or Interpolated
(3) Vendor Brochure
(4) AF Data

Appendix B

Table 23. Rolling Contact Fatigue Tests - VIM VAR Super Nitralloy.
(Test Series B)

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	4,036,220
2	7,845,000
3	3,853,000
4	3,380,140
5	5,265,400
6	3,050,200
7	1,582,180
8	5,030,200
9	2,596,200
10	3,988,340
11	3,831,100
12	4,144,200
13	2,041,860
14	6,000,800
15	3,857,400
16	8,762,660
17	7,991,000
18	2,979,400
19	6,016,520
20	6,573,800

Weibull Analysis

B-10 Life: 2.44 x 10^6 cycles
B-50 Life: 4.69 x 10^6 cycles
Slope: 2.89

Table 24. Rolling Contact Fatigue Tests - Air Melted, Nitralloy 135.
(Test Series v)

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	8,608,300
2	3,641,600
3	7,772,640
4	8,706,600
5	7,397,000
6	2,467,840
7	1,732,600
8	7,748,600
9	2,566,640
10	3,686,400
11	4,520,200
12	5,639,340
13	19,583,600
14	5,557,200
15	4,055,120
16	1,839,900
17	4,873,200
18	586,920
19	2,395,600
20	7,160,600
21	4,281,000
22	6,513,310
23	3,788,400
24	2,323,240
25	2,591,560
26	953,400
27	2,758,000
28	5,236,280
29	4,028,200
30	3,466,520

Weibull Analysis

B-10 Life: 1.43×10^6 cycles
B-50 Life: 4.37×10^6 cycles
Slope: 1.68

Table 25. Rolling Contact Fatigue Tests -- VAR, VASCO Matrix II.

(Test Series w)

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	6,131,200
2	7,356,600
3	16,001,400
4	5,195,000
5	11,111,000
6	5,321,980
7	7,274,400
8	8,111,400
9	15,953,300
10	4,442,200
11	10,240,400
12	10,798,200
13	12,422,920
14	2,745,800
15	7,169,840
16	10,600,800
17	7,199,200
18	2,863,000
19	6,832,600
20	6,852,600

Weibull Analysis

B-10 Life: 3.60×10^6 cycles
B-50 Life: 8.03×10^6 cycles
Slope: 2.35

Table 26. Rolling Contact Fatigue Tests - VAR, AISI 9310.
(Test Series x)

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	18,885,000
2	37,222,200 suspended
3	36,117,080 suspended
4	18,622,600
5	37,982,600 suspended
6	36,669,000 suspended
7	34,875,000
8	16,965,000
9	36,008,400 suspended
10	36,235,400 suspended
11	6,204,000
12	36,057,080 suspended
13	29,134,600
14	36,142,000 suspended
15	36,099,380 suspended
16	36,044,600 suspended
17	37,971,600 suspended
18	36,072,000 suspended
19	36,830,400 suspended
20	37,523,500 suspended

Weibull Analysis

B-10 Life: 14.82 x 10^6 cycles
B-50 Life: 61.50 x 10^6 cycles
Slope: 1.32

Table 27. Rolling Contact Fatigue Tests - Air Melted, CBS 600.

(Test Series y)

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	8,040,000	
2	11,999,800	
3	13,082,640	
4	18,218,400	
5	5,421,220	
6	18,225,000	
7	17,238,800	suspended
8	25,516,200	
9	10,914,040	
10	14,004,460	
11	15,003,200	
12	12,547,720	
13	5,000,400	
14	36,002,400	suspended
15	19,958,720	
16	18,825,200	
17	17,827,540	
18	31,601,400	
19	15,403,360	
20	20,801,700	

Weibull Analysis

B-10 Life: 7.21 x 10^6 cycles
B-50 Life: 16.39 x 10^6 cycles
Slope: 2.29

Table 28. Rolling Contact Fatigue Tests - VAR, CBS 1000M.
(Test Series z)

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	1,879,000
2	3,160,120
3	2,324,400
4	2,386,540
5	1,145,200
6	542,[illegible]
7	1,465,[illegible]
8	1,333,700
9	2,624,200
10	1,598,700
11	1,727,800
12	1,924,740
13	3,404,000
14	1,762,320
15	2,566,880
16	1,780,200
17	2,172,200
18	2,660,000
19	1,640,080

Weibull Analysis

B-10 Life: 1.00×10^6 cycles
B-50 Life: 1.99×10^6 cycles
Slope: 2.73

Table 29. Rolling Contact Fatigue Tests - VAR, AISI W-1.
(Test Series α)

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	16,027,400	
2	9,708,000	
3	35,942,480	suspended
4	12,432,000	
5	34,100,000	
6	36,508,000	suspended
7	16,279,000	
8	4,781,800	
9	17,656,020	
10	30,450,800	
11	15,549,000	
12	17,260,200	
13	36,489,700	suspended
14	2,658,600	
15	10,877,600	
16	22,950,000	
17	18,878,400	
18	11,266,600	
19	23,640,000	
20	34,528,600	

Weibull Analysis

B-10 Life: 5.95×10^6 cycles
B-50 Life: 19.68×10^6 cycles
Slope: 1.58

Table 30. Rolling Contact Fatigue Tests - VAR, AISI 0-2.
(Test Series β)

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	10,805,000	
2	19,800,000	
3	36,270,700	suspended
4	11,199,000	
5	13,320,000	
6	14,764,380	
7	15,990,000	
8	2,043,000	
9	36,470,460	suspended
10	18,482,200	
11	16,175,000	
12	37,951,180	suspended
13	19,855,000	
14	1,909,500	
15	37,530,940	suspended
16	6,278,400	
17	35,610,000	suspended
18	8,726,460	
19	26,850,000	
20	37,128,500	suspended

Weibull Analysis

B-10 Life: 5.10×10^6 cycles
B-50 Life: 18.70×10^6 cycles
Slope: 1.45

Table 31. Rolling Contact Fatigue Tests - VAR, AISI S-2.
(Test Series γ)

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	6,210,000
2	4,430,000
3	13,067,400
4	11,275,000
5	1,200,000
6	26,525,420
7	2,385,000
8	4,865,500
9	7,533,820
10	5,805,000
11	1,305,000
12	19,353,920
13	4,860,000
14	11,895,000
15	6,298,820
16	7,230,000
17	4,275,000
18	1,673,800
19	2,477,400
20	3,240,000

Weibull Analysis

B-10 Life: 1.23×10^6 cycles
B-50 Life: 5.41×10^6 cycles
Slope: 1.27

Table 32. Rolling Contact Fatigue Tests - VAR, VASCO X-2.

(Test Series δ)

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	7,288,200
2	20,600,600
3	28,898,200
4	6,562,800
5	9,999,800
6	22,051,200
7	5,440,200
8	10,905,000
9	31,485,360
10	12,797,800
11	15,856,000
12	30,608,620
13	14,385,200
14	21,694,640
15	17,058,800
16	13,883,500
17	8,488,600
18	6,511,600
19	16,192,600
20	15,664,200

Weibull Analysis

B-10 Life: 6.31×10^6 cycles
B-50 Life: 15.13×10^6 cycles
Slope: 2.16

Table 33. Rolling Contract Fatigue Test - VAR, Nitralloy N.

(Test Series [illegible])

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	7,845,000
2	7,899,400
3	2,265,600
4	4,980,000
5	5,408,400
6	7,804,000
7	6,585,000
8	4,510,800
9	7,066,460
10	4,155,000
11	5,370,600
12	3,496,640
13	1,875,000
14	5,340,000
15	2,125,380
16	4,025,000
17	7,995,000
18	2,404,940
19	5,465,000
20	3,600,000

Weibull Analysis

B-10 Life: 2.30×10^6 cycles
B-50 Life: 4.90×10^6 cycles
Slope: 2.48

Table 34. Rolling Contact Fatigue Tests - VIM-VAR, AISI 9310.
(Test Series AA)

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	10,920,000
2	18,650,000
3	8,895,000
4	7,830,000
5	7,950,000
6	9,345,000
7	6,600,000
8	7,920,000
9	9,870,000
10	19,170,000

Weibull Analysis

B-10 Life: 5.25 x 10^6 cycles
B-50 Life: 10.65 x 10^6 cycles
Slope: 2.66

Table 35. Rolling Contact Fatigue Tests - VAR, CBS 1000M*.

(Test Series AB)

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	3,630,000
2	5,295,000
3	2,637,440
4	9,195,000
5	4,605,000
6	5,280,000
7	11,970,000
8	9,980,000
9	7,230,000
10	4,440,000

Weibull Analysis

B-10: 2.71×10^6 cycles
B-50: 6.22×10^6 cycles
Slope: 2.27

*Heat treated by Timken Company

Table 36. Rolling Contact Fatigue Tests - VAR, CBS 1000M.

(Test Series AC)

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	3,345,000
2	2,450,000
3	3,675,000
4	4,365,000
5	5,700,000
6	3,705,000
7	5,970,000
8	1,950,000
9	3,495,000
10	6,135,000

Weibull Analysis

B-10 Life: 2.11×10^6 cycles
B-50 Life: 4.05×10^6 cycles
Slope: 2.89

Table 37. Rolling Contact Fatigue Tests - VAR, CBS 600.

(Test Series AD)

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	34,500,000 suspended
2	5,850,000
3	12,135,000
4	6,825,000
5	18,150,000
6	12,210,000
7	9,870,000
8	10,575,000
9	36,000,000 suspended
10	5,925,000

Weibull Analysis

B-10 Life: 5.16×10^6 cycles
B-50 Life: 11.76×10^6 cycles
Slope: 2.29

Table 38. Rolling Contact Fatigue Tests - VAR, CBS 600.
(Test Series AE)

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	14,610,000
2	7,050,000
3	7,215,000
4	15,045,000
5	5,150,000
6	14,805,000
7	12,255,000
8	11,055,000
9	10,860,000
10	12,235,000

Weibull Analysis

B-10 Life: 5.81×10^6 cycles
B-50 Life: 11.01×10^6 cycles
Slope: 2.95

Table 39. Rolling Contact Fatigue Tests - VAR, CBS 600.

(Test Series AF)

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	6,270,000
2	7,800,000
3	15,540,000
4	15,600,000
5	4,250,000
6	5,025,000
7	16,365,000
8	9,859,999
9	14,024,000
10	5,430,000

Weibull Analysis

B-10 Life: 3.79×10^6 cycles
B-50 Life: 9.61×10^6 cycles
Slope: 2.02

Table 40. Rolling Contact Fatigue Tests - VAR, AISI 9310.
(Base Line Test)

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	12,240,000
2	11,250,000
3	10,500,000
4	3,690,000
5	10,500,000
6	5,130,000
7	9,660,000
8	7,300,000
9	19,544,000
10	7,170,000

Weibull Analysis

B-10 Life: 4.18 x 10^6 cycles
B-50 Life: 9.43 x 10^6 cycles
Slope: 2.31

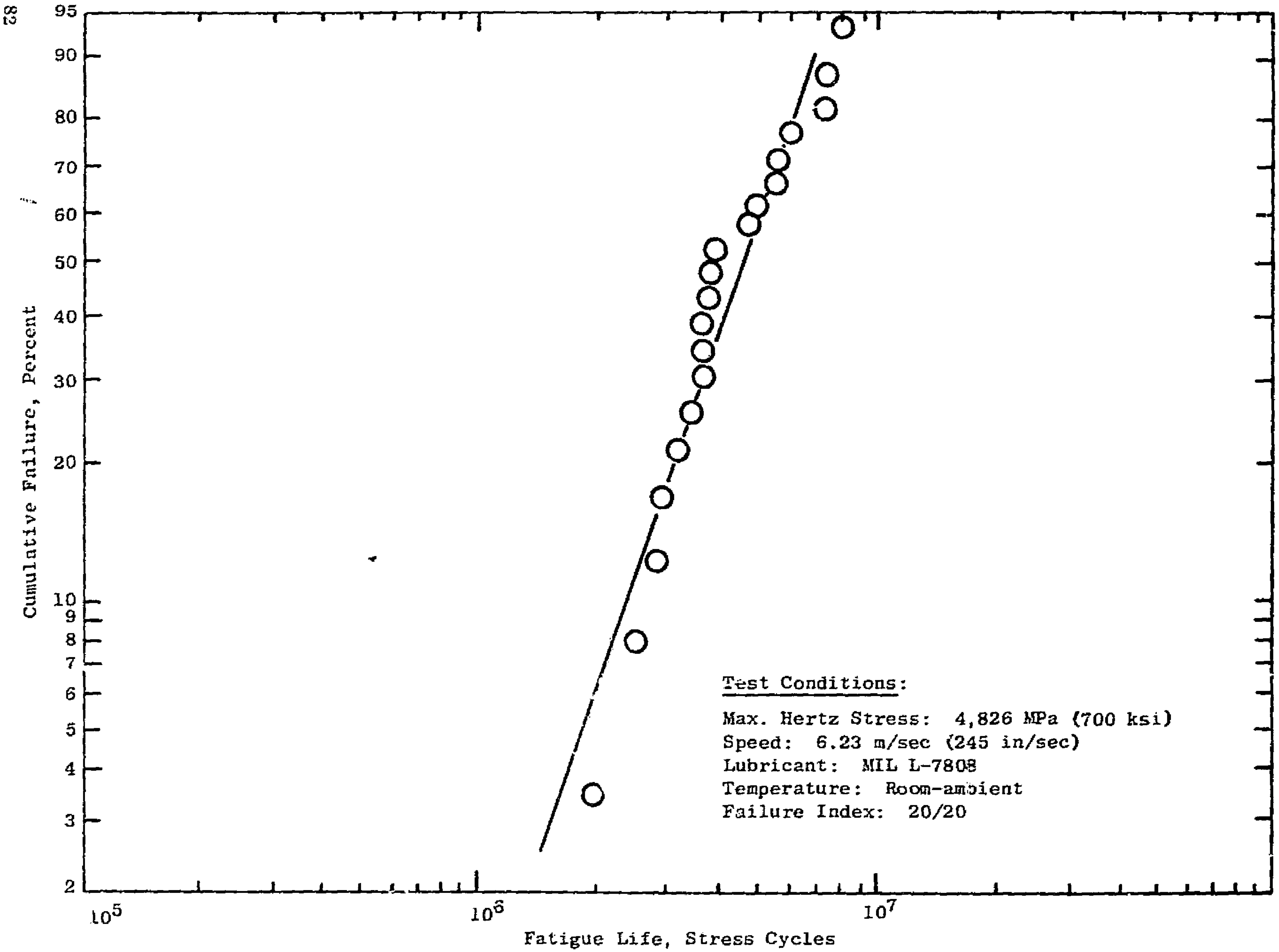

FIGURE 34. RCF Test Results of VIM-VAR Super Nitralloy (Test Series u)

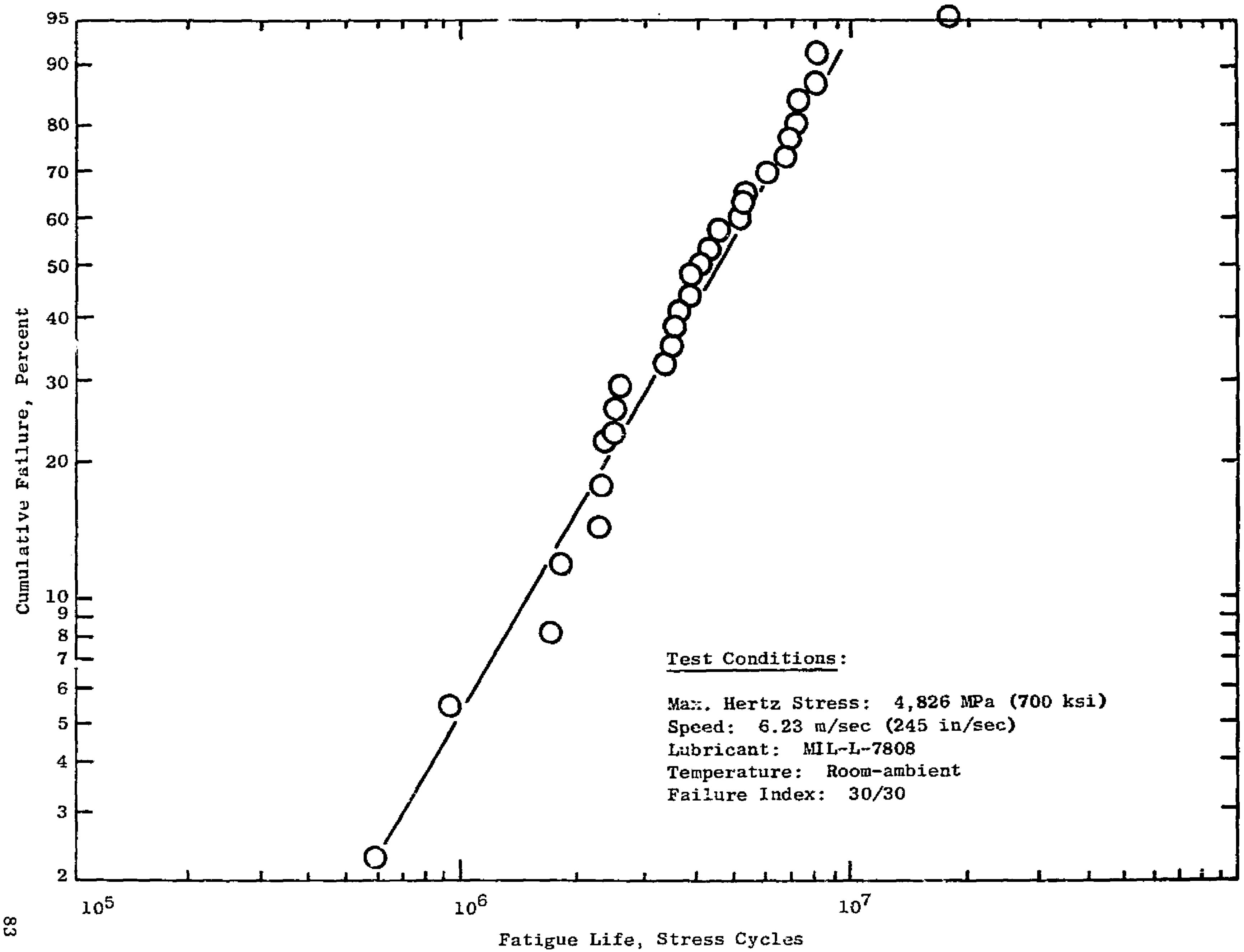

FIGURE 35. RCF Test Results of Air Melted, Nitralloy 135 (Test Series v)

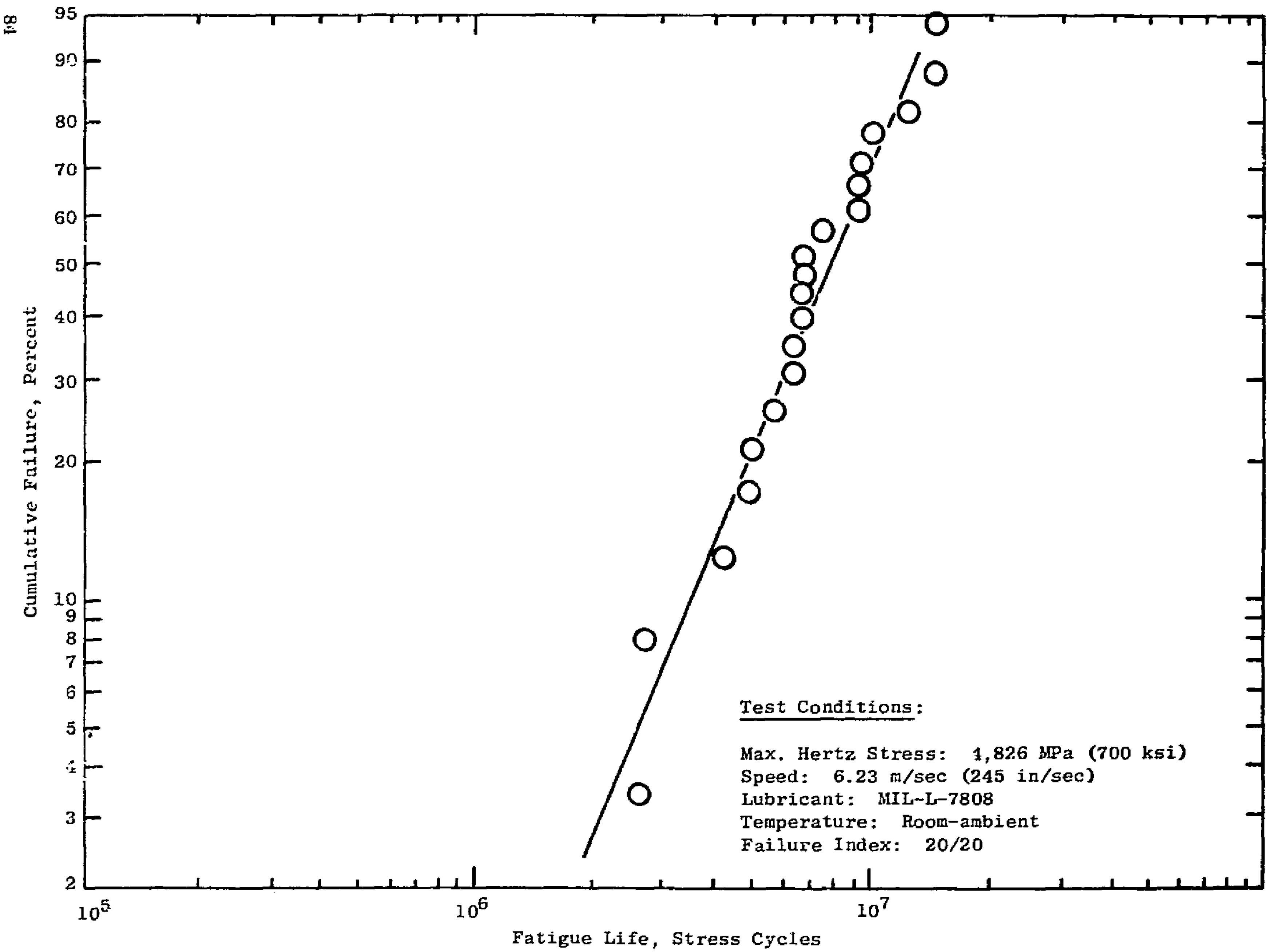

FIGURE 36. RCF Test Results of VAR, Vasco Matrix II (Test Series w)

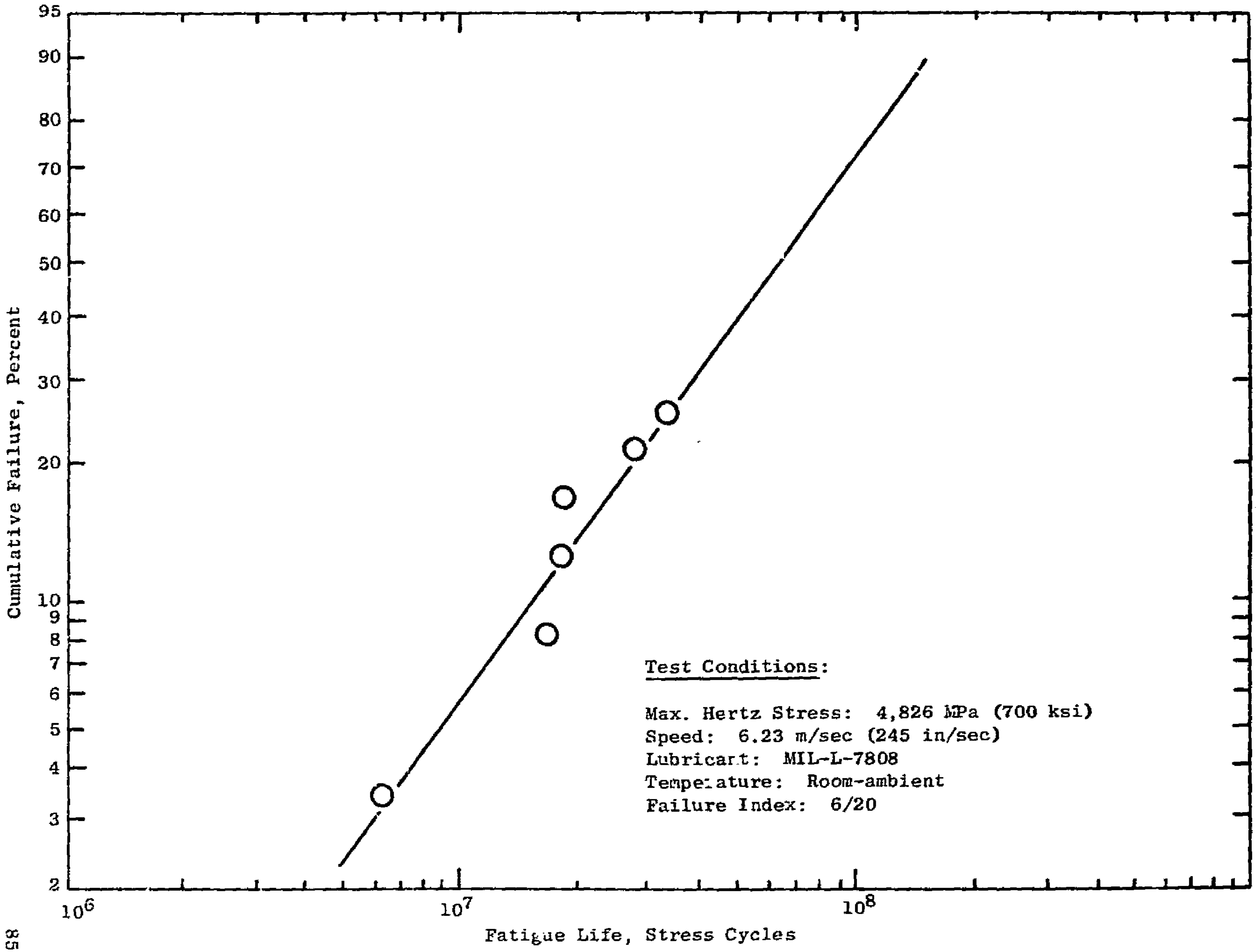

FIGURE 37. RCF Test Results of VAR, AISI 9310 (Test Series x)

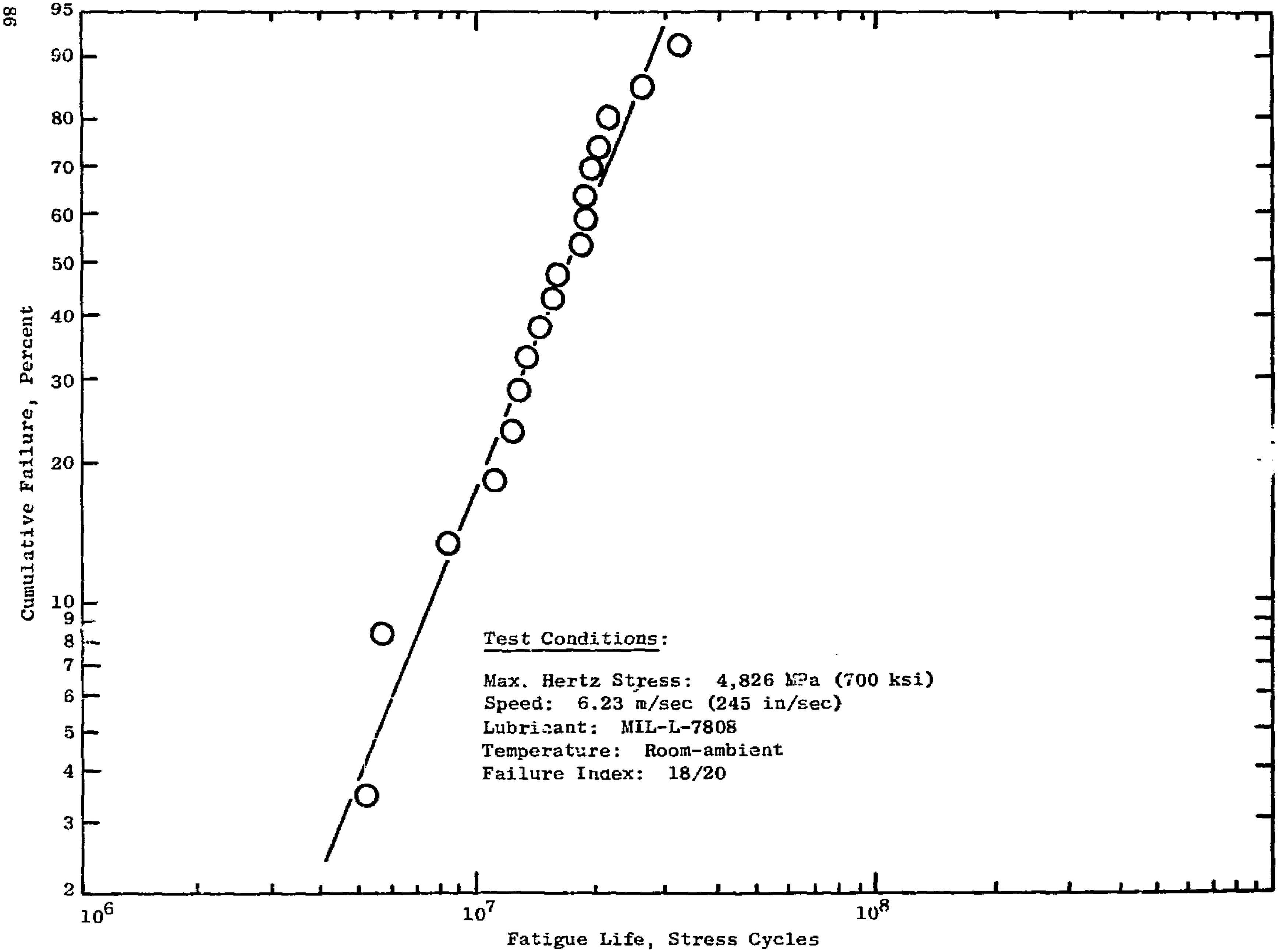

FIGURE 38. RCF Test Results of Air Melted CBS 600 (Test Series y)

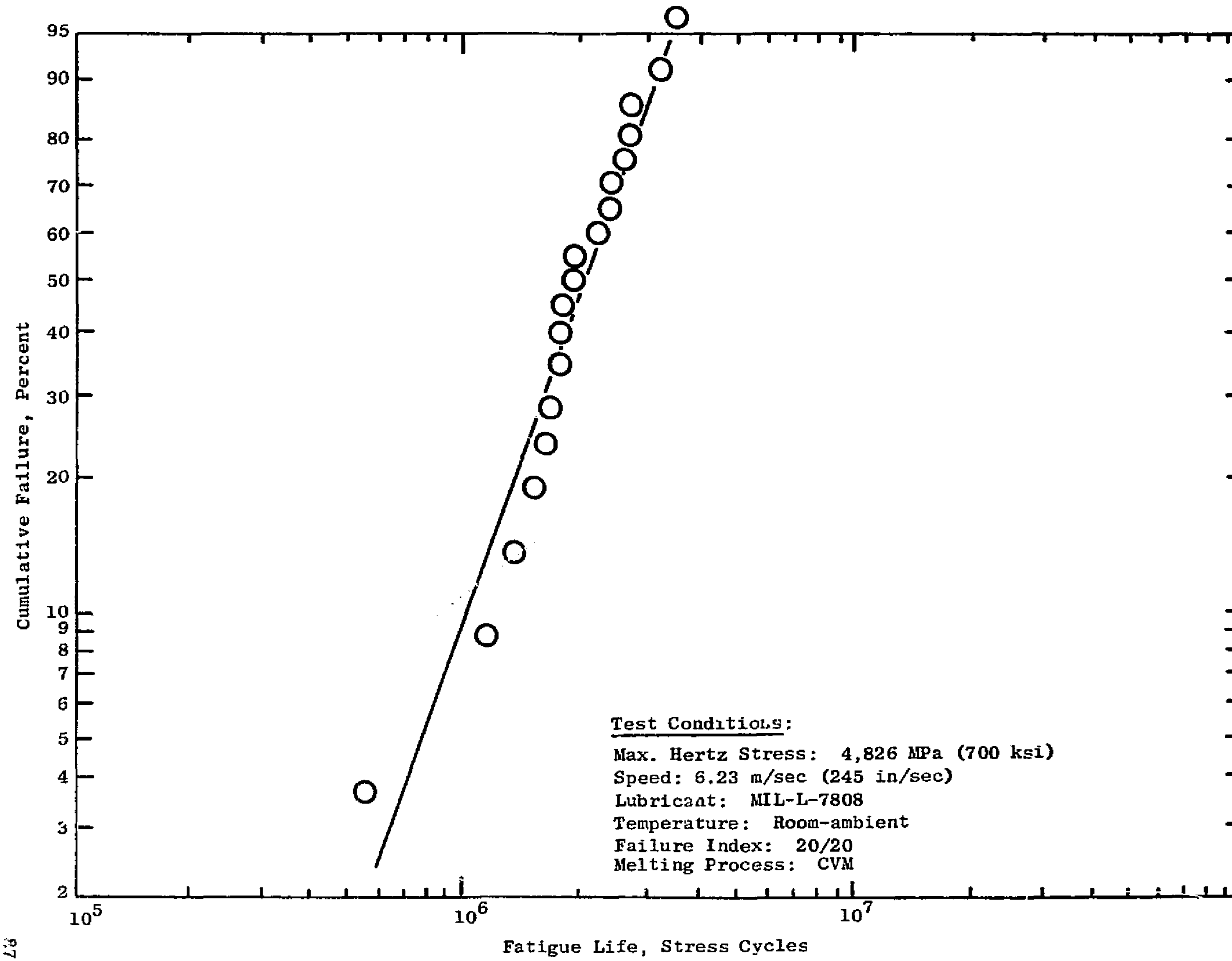

FIGURE 39. RCF Test Results of VAR CBS 1000M (Test Series z)

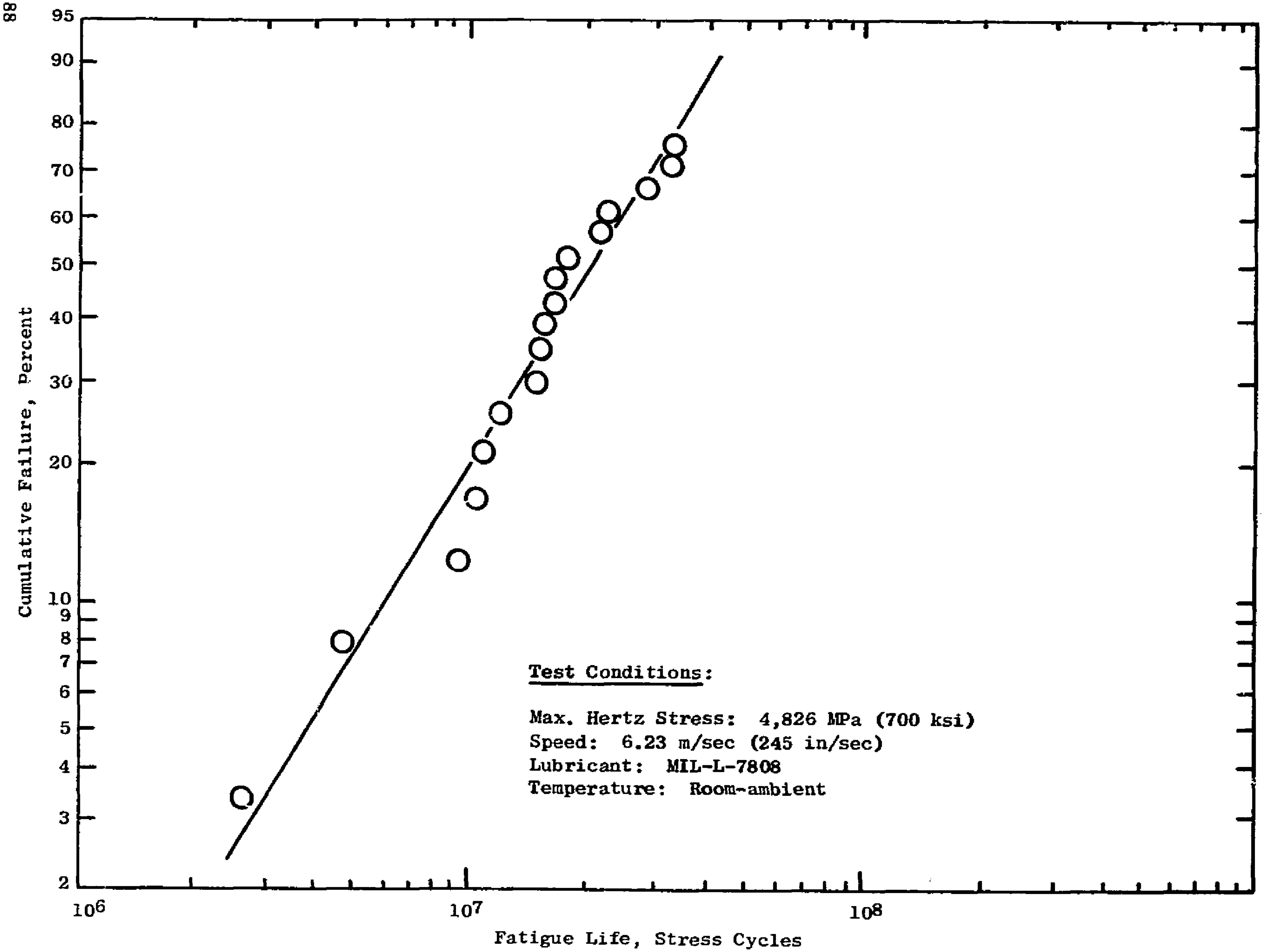

FIGURE 40. RCF Test Results of VAR, AISI W-1 (Test Series α)

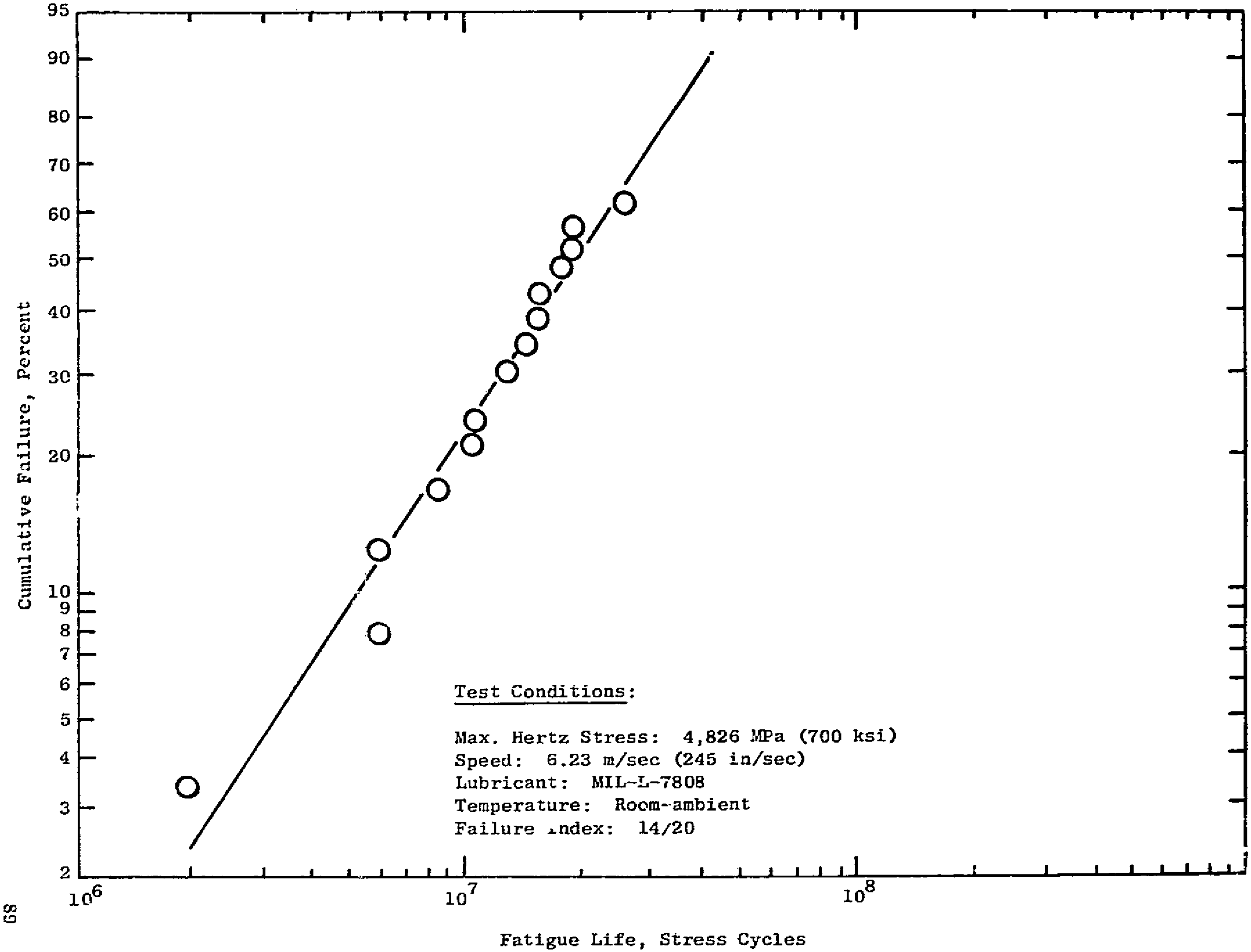

FIGURE 41. RCF Test Results of VAR, AISI 0-2 (Test Series β)

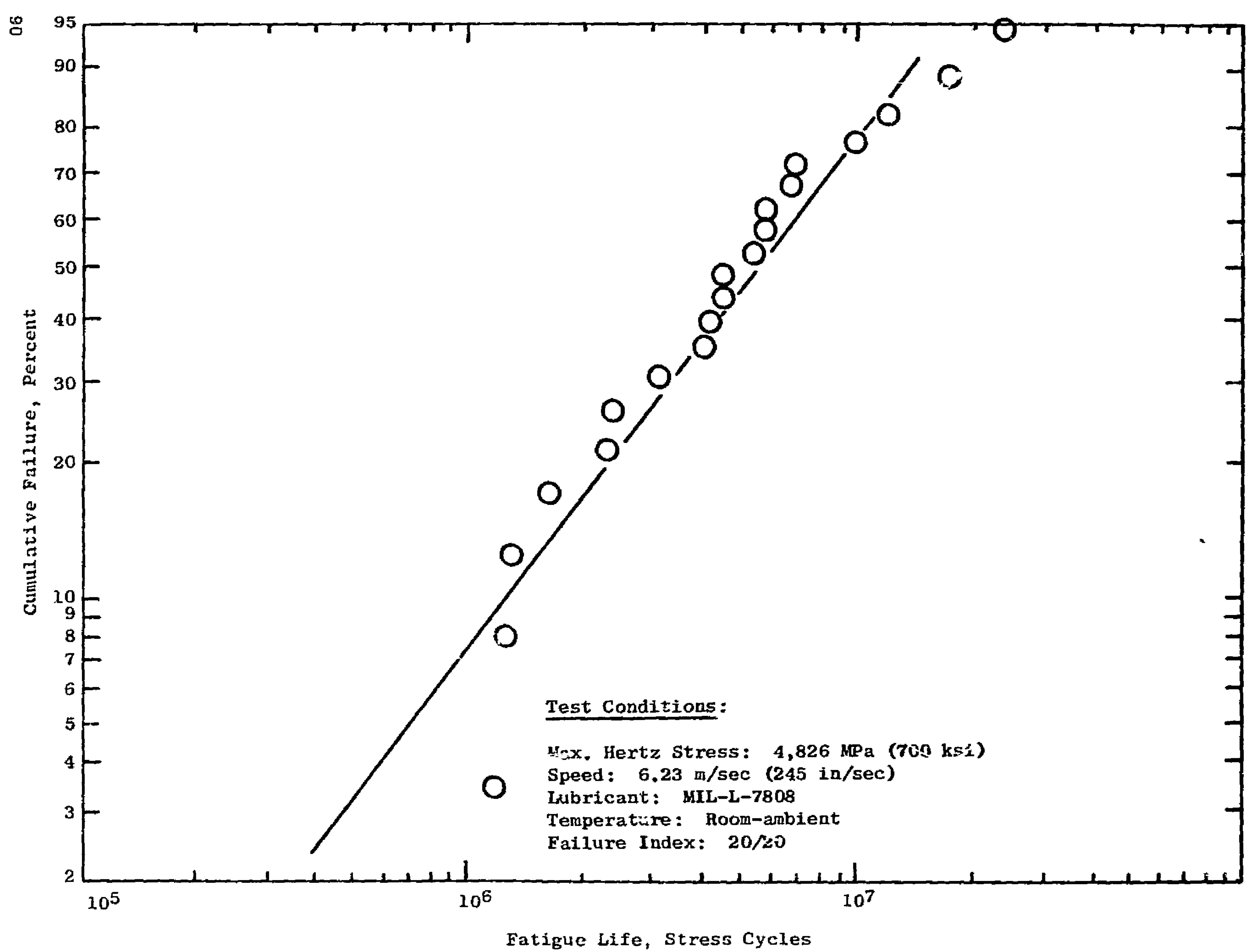

FIGURE 42. RCF Test Results of VAR, AISI S-2 (Test Series γ)

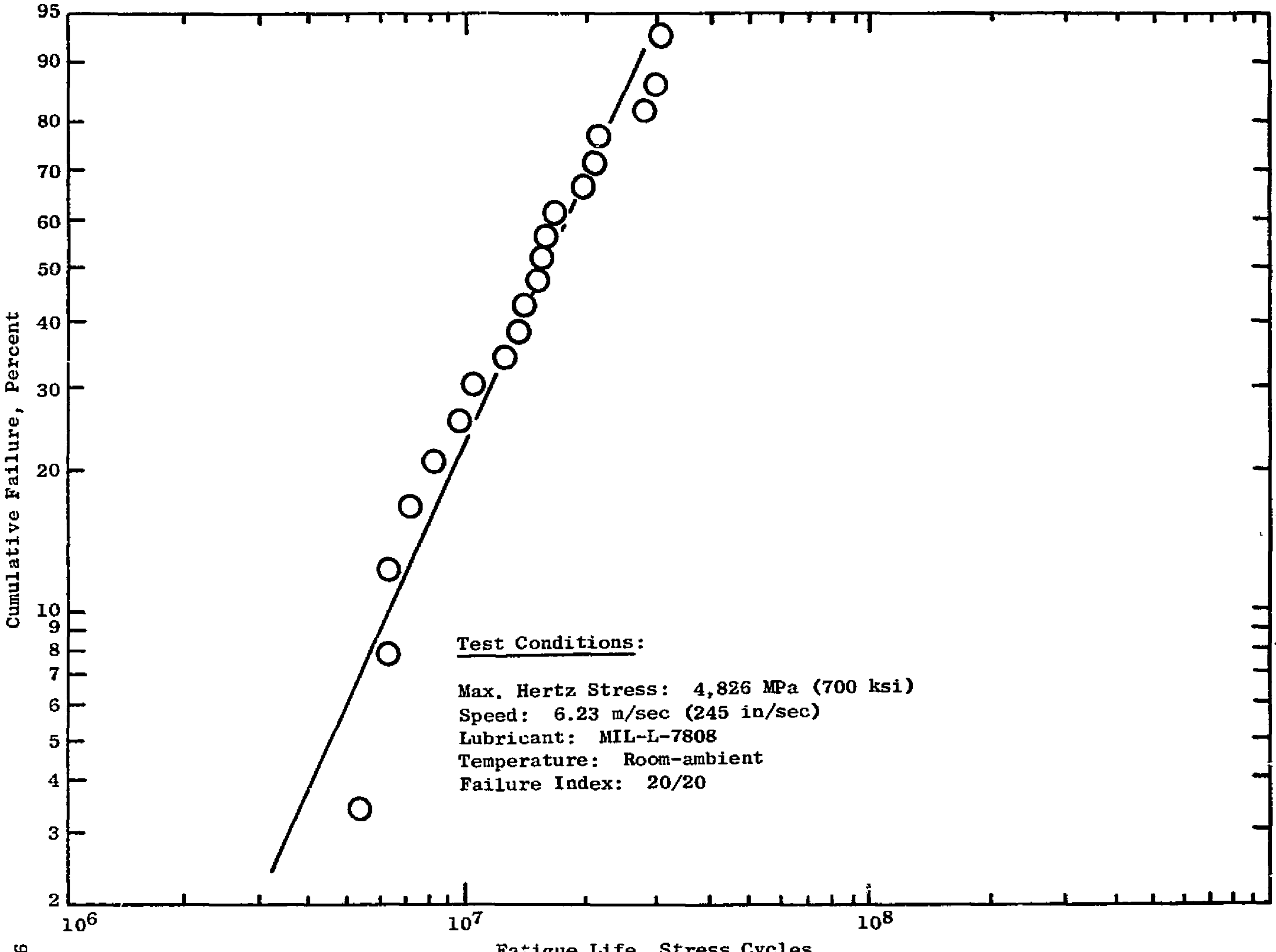

FIGURE 43. RCF Test Results of VAR, Vasco X-2. (Test Series δ)

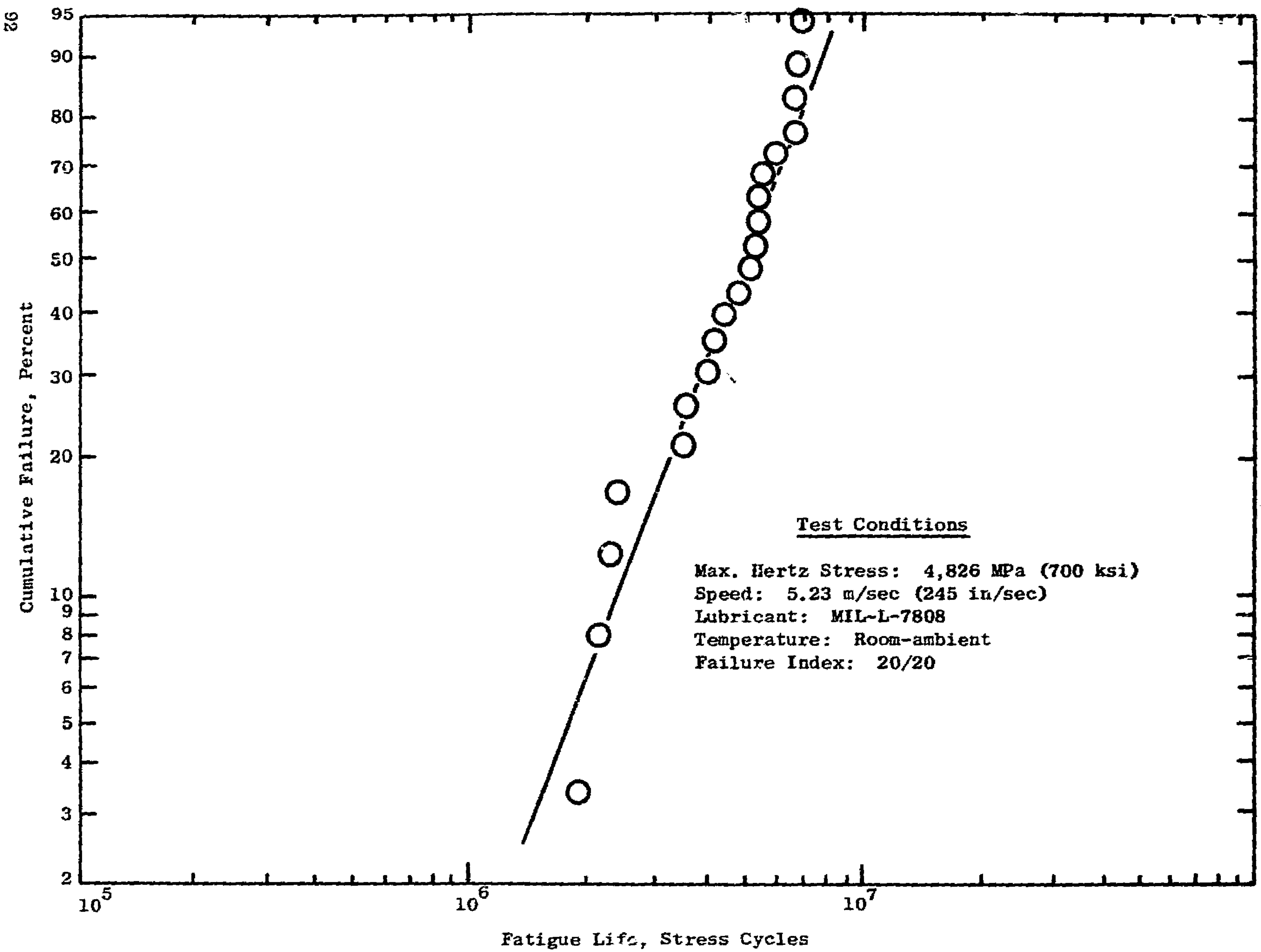

FIGURE 44. RCF Test Results of VAR Nitralloy N (Test Series ϵ)

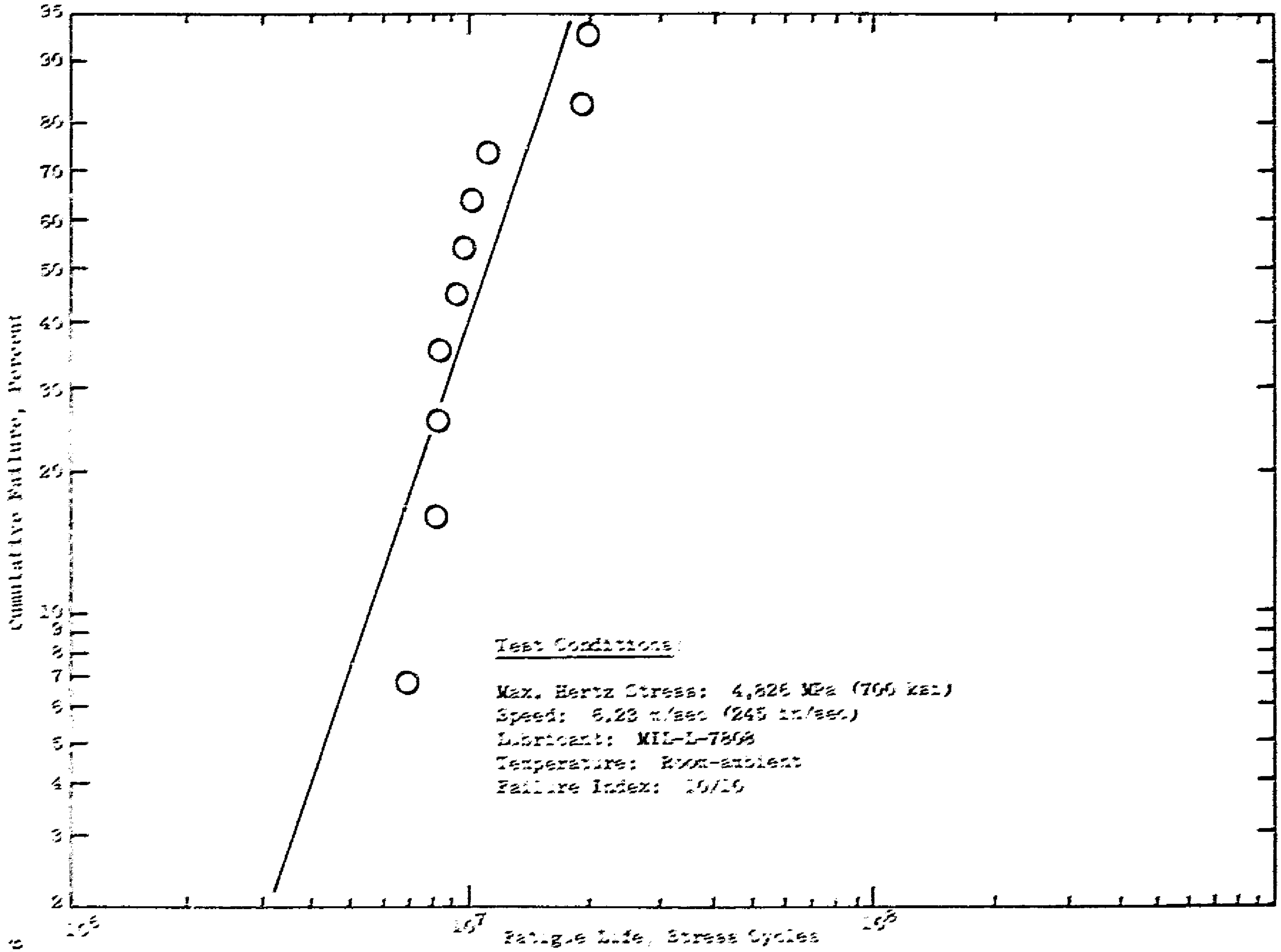

FIGURE 45. RCF Test Results of VIM-VAR AISI 9310 (Test Series AA)

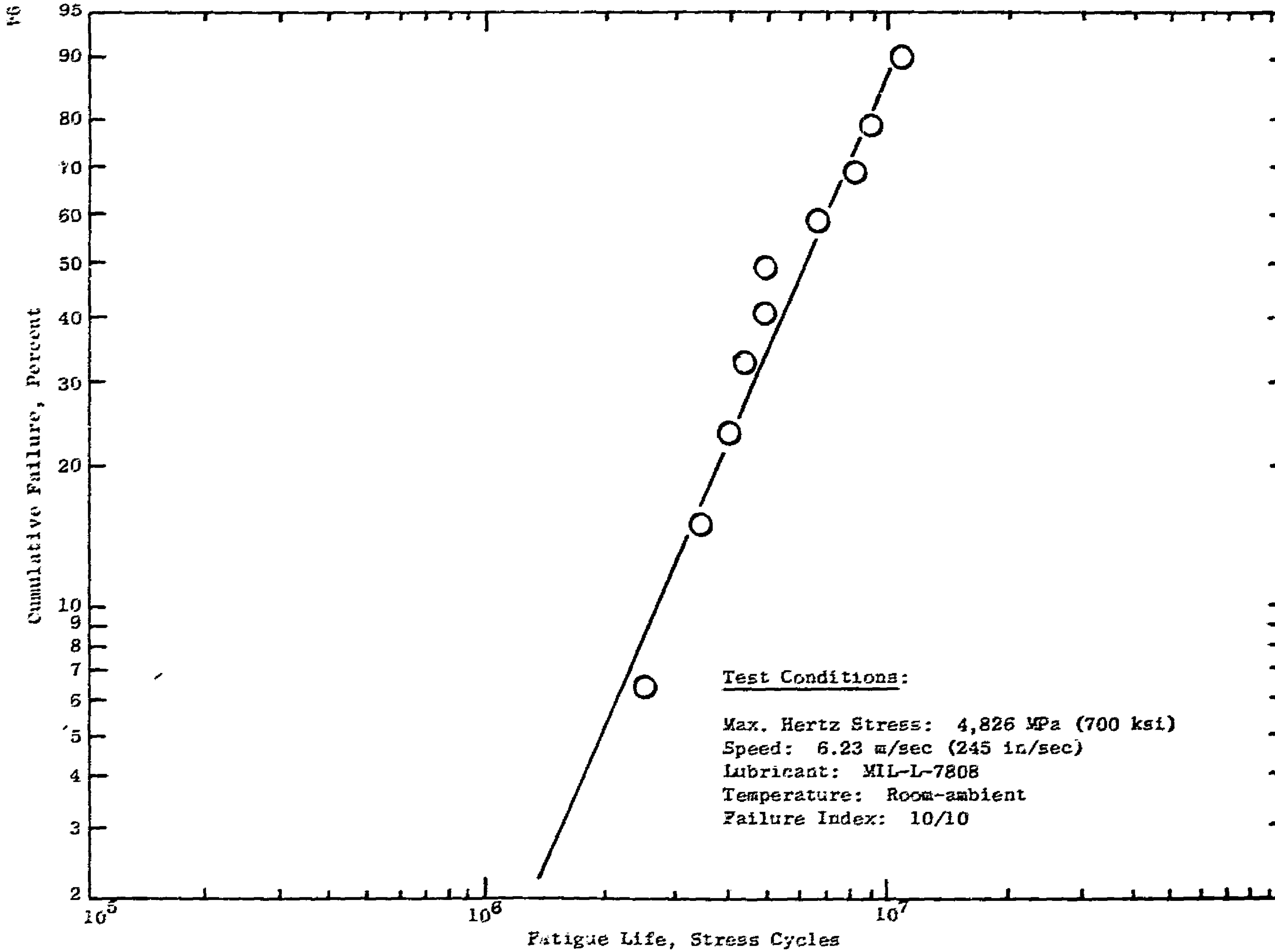

FIGURE 46. RCF Test Results of VAR, CBS-1000M (Test Series AB)

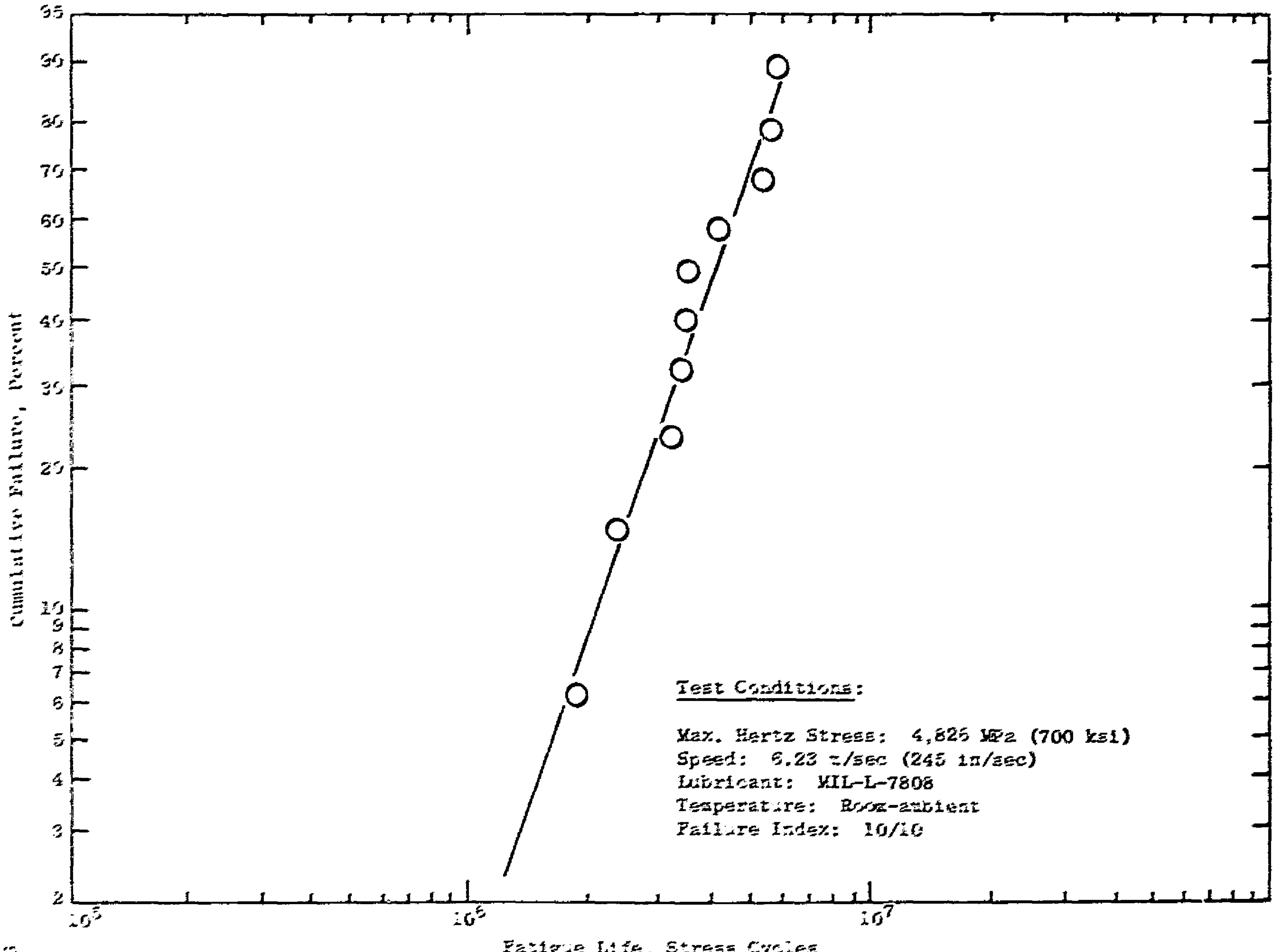

FIGURE 47. RCF Test Results of VAR, CBS-1000M (Test Series AC)

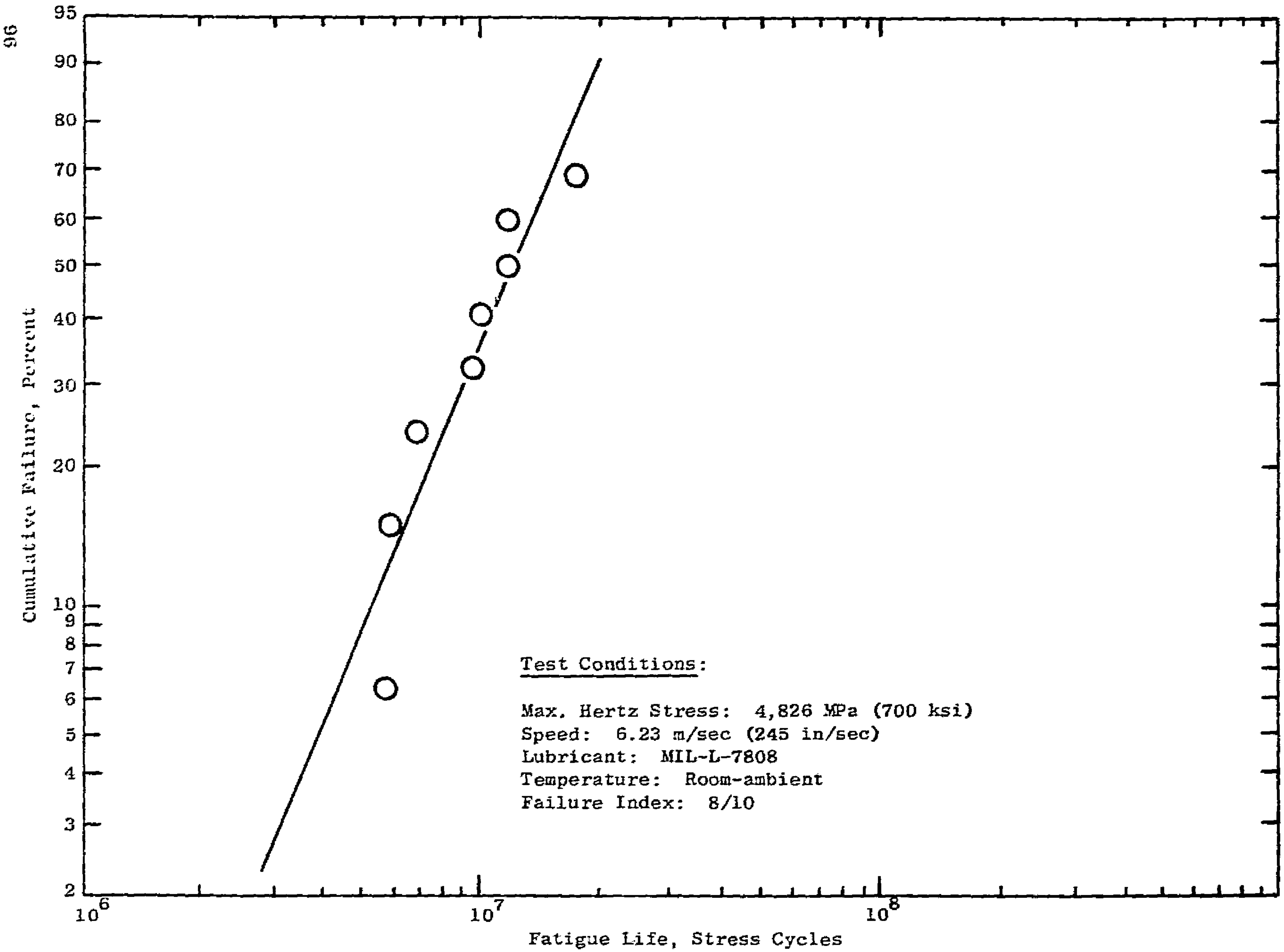

FIGURE 48. RCF Test Results of VAR, CBS 600 (Test Series AD)

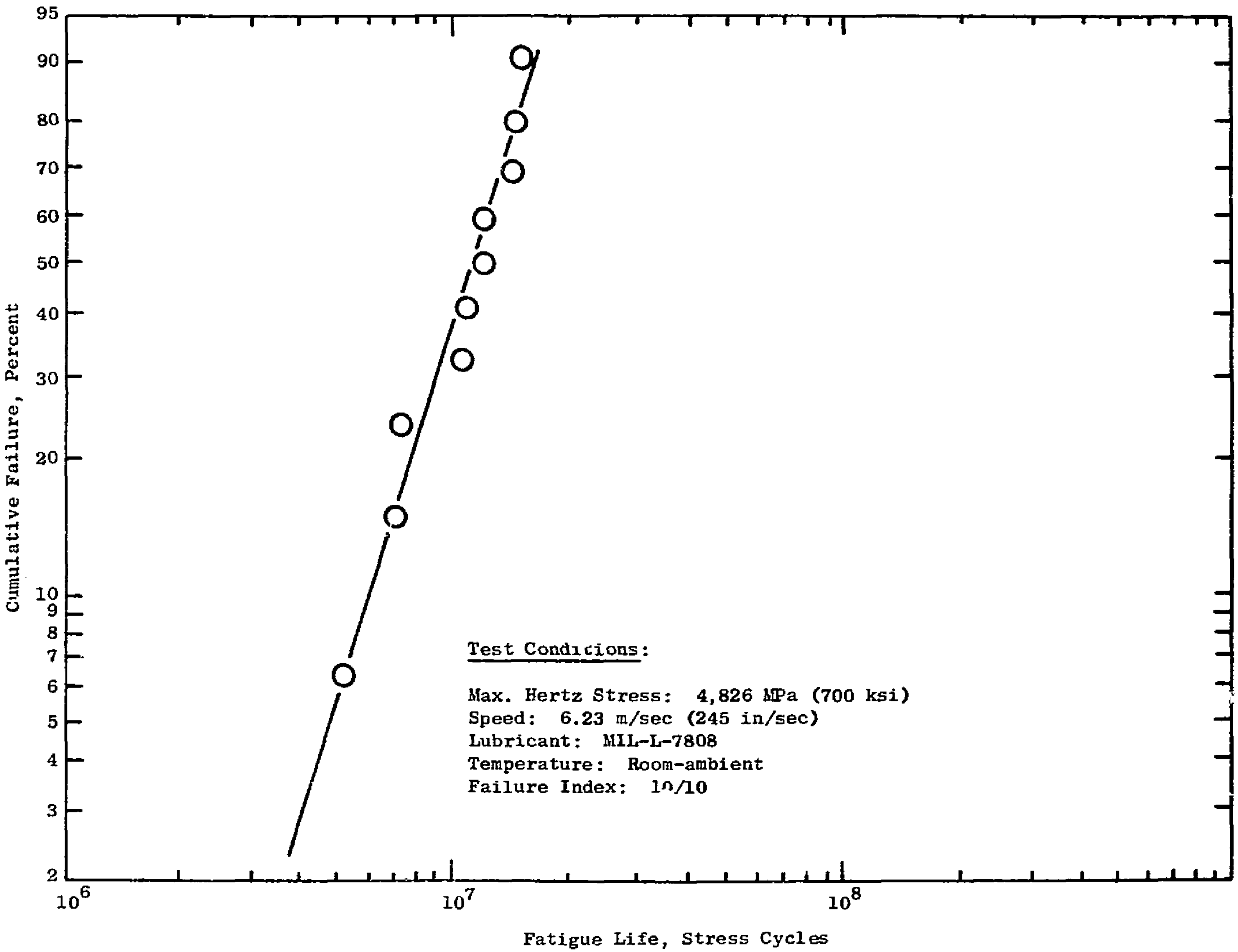

FIGURE 49. RCF Test Results of VAR, CBS 600 (Test Series AE)

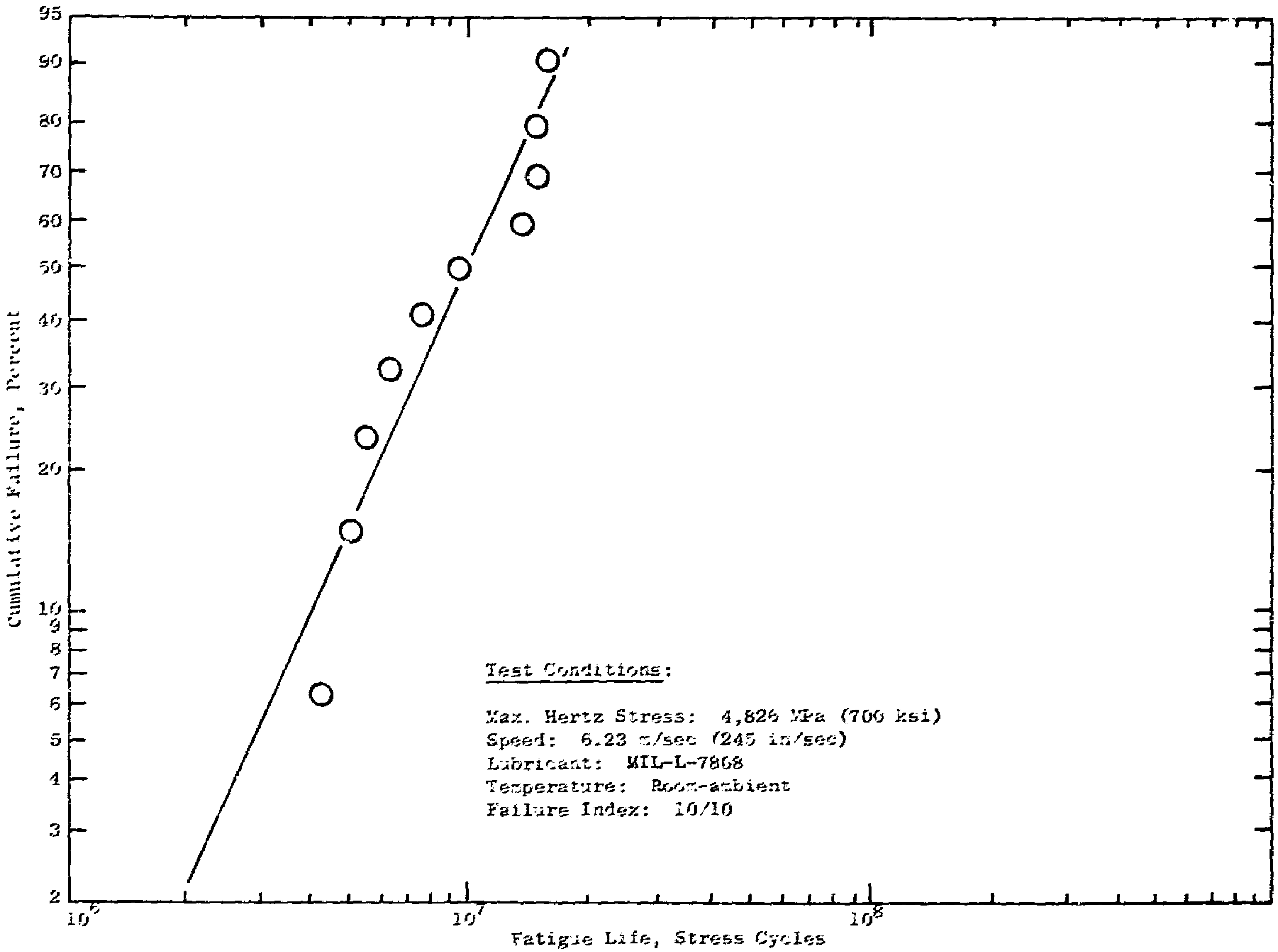

FIGURE 50. RCF Test Results of VAR, CBS 600 (Test Series AF)

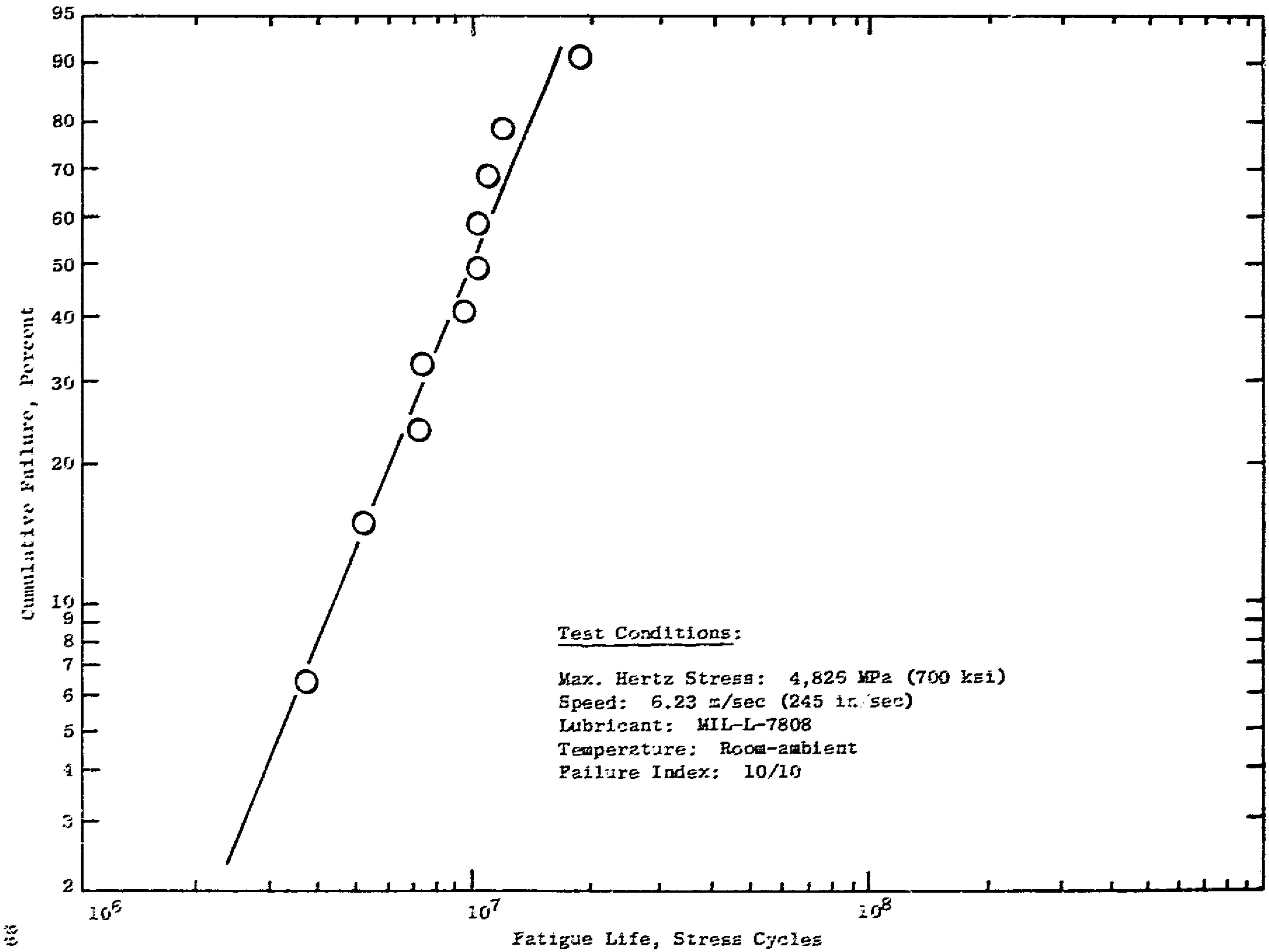

FIGURE 51. RCF Test Results of VAR AISI 9310 (Baseline)

Appendix C

Table 41. Summary of RCF Test Results of Test Materials for Phase I[(a)].

Test Series	Test Materials (Melting Process)	B-10 Life $x10^6$ Cycles	B-50 Life $x10^6$ Cycles	Weibull Slope	Failure[(c)] Index
u	Super Nitralloy (VIM-VAR)[(b)]	2.44	4.69	2.89	20/20
v	Nitralloy 135 (Air Melted)	1.43	4.37	1.68	30/30
w	Matrix II (CVM)	3.60	8.03	2.35	20/20
x	AISI 9310 (CVM)	14.82	61.50	1.32	6/20
y	CBS 600 (Air Melted)	7.20	16.39	2.29	18/20
z	CBS 1000M (CVM)	1.00	1.99	2.78	20/20
α	AISI W-1 (CVM)	5.95	19.68	1.58	17/20
β	AISI O-2 (CVM)	5.10	18.70	1.45	14/20
γ	AISI S-2 (CVM)	1.23	5.41	1.27	20/20
δ	Vasco X-2 (CVM)	6.31	15.13	2.16	20/20
ε	Nitralloy N (CVM)	2.30	4.91	2.48	20/20
Base Line	AISI M50[(d)] (VIM-VAR)	3.80	6.30	3.30	250/250

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

(b) Melting Process

(c) Number of failures out of total number of tests.

(d) 12 heats of M50 were tested.

Table 42. Summary of RCF Test Results of Test Materials for Phase II[a].

Test Series	Test Materials (Melting Process)	B-10 Life $x10^6$ Cycles	B-50 Life $x10^6$ Cycles	Weibull Slope	Failure[c] Index
AA	AISI 9310 (VIM-VAR)	5.25	10.65	2.66	10/10
AB	CBS 1000M (CVM) (Timken)	2.71	6.22	2.27	10/10
AC	CBS 1000M (CVM) (GE)	2.11	4.05	2.89	10/10
AD	CBS 600 (CVM)	5.16	11.76	2.29	8/10
AE	CBS 600 (CVM)	5.81	11.01	2.95	10/10
AF	CBS 600 (CVM)	3.79	9.61	2.02	10/10
Base Line	AISI 9310 (CVM)	4.18	9.43	2.31	10/10

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

(b) Melting Process

(c) Number of failures out of the total number of tests.

Appendix D

Table 43. Summary of Metallurgical Characteristics of Test Materials for Phase I.

Test Series	Test Materials (Melting Process)	Effective Case Depth[d] mm (in.)	Surface Hardness[a] HRC	Core Hardness HRC	Retained[b] Austenite %
u	Super Nitralloy (VIM-VAR)	0.43 (0.017)	60.4	42.0	4.8
v	Nitralloy 135 (Air Melted)	0.38 (0.015)	60.6	35.0	N.D.[c]
w	Matrix II (CVM)	--- ---	62.6	---	1.2
x	AISI 9310 (CVM)	0.[illegible] (0.030)	60.4	41.0	20.1
y	CBS 600 (Air Melted)	0.76 (0.030)	65.0	44.0	8.7
z	CBS 1000M (CVM)	0.76 (0.030)	60.1	45.0	N.D.
α	AISI W-1 (CVM)	--- ---	61.2	---	6.6
β	AISI O-2 (CVM)	--- ---	62.3	---	9.6
γ	AISI S-2 (CVM)	--- ---	60.4	---	1.2
δ	Vasco X-2 (CVM)	0.89 (0.035)	60.0	43.0	22.0
ε	Nitralloy N (CVM)	0.38 (0.015)	62.9	46.0	N.D.

(a) Rockwell Superficial 15-N were measured on each finished test bar and converted to HRC.
(b) Measured on the surface of finished test bars by X-ray diffraction analysis.
(c) N.D. represents "not detected."
(d) Depth below the surface at which HRC 58 occurs.

Table 44. Summary of Metallurgical Characteristics of Test Materials for Phase II.

Test Series	Test Materials (Melting Process)	Effective Case Depth[d] mm (in.)	Surface Hardness[a] HRC	Core Hardness HRC	Retained[b] Austenite %
AA	AISI 9310 (VIM VAR)	0.84 (0.033)	60.2	38.0	8.3
AB	CBS 1000M (VIM) (Timken)	1.09 (0.043)	61.6	47.0	1.7
AC	CBS 1000M (VIM) (G.E.)	[illegible]	60.9	47.0	[illegible]
AD	CBS 600 (VIM)	0.84 (0.033)	61.7	40.0	4.3
AE	CBS 600 (VIM)	0.84 (0.033)	60.3	40.0	3.4
AF	CBS 600 (VIM)	0.84 (0.0[illegible])	61.6	40.0	2.3
Base line	AISI 9310 (VIM)	0.84 (0.033)	61.4	38.0	11.2

(a) Rockwell Superficial 15-N were measured on each finished test bar and converted to HRC.

(b) Measured on the surface of finished test bars by X-ray diffraction analysis.

(d) Depth below the surface at which HRC 58 occurs.