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CERAMIC BEARING DEVELOPMENT
SILICON NITRIDE BEARING BALLS OF IMPROVED RELIABILITY: THERMAL OXIDATION

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13. ABSTRACT *(Maximum 200 words)*

The major objective of this work was to improve the reliability of silicon nitride bearing balls by means of an optimized thermal oxidation treatment. Previous work had shown that the thermal fracture resistance of silicon nitride bearing balls increased when the balls were heated and oxidized in air.

An optimized oxidation treatment for NBD-200 silicon nitride balls was developed, using a thermal proof test matrix. This oxidation treatment increased the thermal fracture resistance of the balls. Ball-on-rod RCF testing of oxidized and non-oxidized balls was performed at 786 KSI contact stress, with nitrided M50-NIL rods.

RCF testing did not produce a significant percentage of ball failures for either the oxidized or non-oxidized condition. Alternative methods, such as four ball fatigue testing, should be considered for future work. The oxidation treatment degraded ball surface and geometry, and is suspected as a contributing factor to short rod life. Oxidation treatment does not appear to be a useful technique for improving the reliability of NBD-200 bearing balls.

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FOREWORD

This report presents results accomplished under an extension of Contract F33615-92-C-5917, Sec. 5.1.2, "Bearing Balls of Improved Reliability - Thermal Proof Test". This work consists of Task 3.2.4, establishing an optimized thermal treatment for silicon nitride bearing balls; and Task 3.2.5, rolling contact fatigue testing of thermally treated silicon nitride bearing balls. Task 3.2.4 was accomplished at the University of Dayton Research Institute, under Subcontract 5227. Professor Leon Chuck, the Principal Investigator, produced the final report: "Development Of A Thermal Proof Test For Silicon Nitride Balls" WL-TR-96-4017. The contributions of Matthew A. Kashuk, George A. Graves, James R. Hoenigman, Thomas N. Wittburg, and J. Doug Wolf are acknowledged. Task 3.2.5 was accomplished at Mechanical Technology Incorporated, under Subcontract 5226. Dr. Roy B. Howarth, the Principal investigator, produced the final report: "Rolling Contact Fatigue With M-50 Nil Rods and NBD-200 Balls". His contributions to program success are acknowledged. Section 5 of this report is mainly his work. The efforts of David S. Jacobs, Saint Gobain/Norton Industrial Ceramics Northboro Research and Development Center, and the guidance of Phillip K. Pearson, of The Torrington Company, are also acknowledged. The efforts of Amy J. Bizon, Wendi L. Carey, and Quentin J.Walker, of Norton Advanced Ceramics are also acknowledged.

The work described herein is specific to Norton Advanced Ceramics NBD-200 silicon nitride and may not represent the capabilities of other silicon nitride materials.

1.0 SUMMARY

This report presents the work accomplished under an extension of Contract F33615-92-C-5917, Sec.5.1.2, " Bearing Balls of Improved Reliability - Thermal Proof Test". In the original work, the thermal fracture resistance of NBD-200 bearing balls increased when the balls were heated and oxidized in air. The additional work, described herein, is a followup study to establish an optimized oxidation treatment for NBD-200 silicon nitride balls, and to determine if an improvement in rolling contact fatigue life could be achieved using this oxidation treatment.

An optimized oxidation treatment for NBD-200 balls was established, using a thermal proof test matrix to establish the time and temperature for oxidation. A trial lot of oxidized 1/2" diameter balls was produced for rolling contact fatigue testing. A control lot of non-oxidized balls was also tested. To precipitate more ball failures than rod failures, the test rods were made from nitrided M-50 NIL, which has been shown to have a very high fatigue life when tested with steel balls.

There was only one ball failure in the non-oxidized tests, and none in the oxidized tests. Overall, the life of the M-50 NIL rods was shorter with the oxidized balls. Degradation of surface finish and geometry of the oxidized balls is suspected as the cause of short rod life.

2.0 INTRODUCTION

The main objective of this work was to investigate the premise that pre-oxidation of silicon nitride balls improves their fatigue life in rolling contact. Previous work had shown that pre-oxidation improved the thermal fracture resistance of silicon nitride balls with induced flaws. The mechanism for this improvement was thought to be micro-crack healing.

Task 3.2.4 established an optimized oxidation treatment for silicon nitride bearing balls. A single manufacturing lot of 1/2" NBD-200 Grade 5 balls, produced from one silicon nitride powder lot, was utilized in this work. The following methods were used to optimize the oxidation treatment. A baseline Weibull plot for the probability of thermal cracking of the balls as a function of thermal quench temperature difference was established. Small samples of balls were oxidized, varying both temperature and relative humidity, while maintaining the oxidation time constant. The response of these small samples to the thermal quench was compared to the baseline data. Small samples of balls were then oxidized, varying the time, while maintaining a selected oxidation temperature constant. The response of these small samples was compared to the baseline data. An "optimum" oxidation treatment was selected, and a sample lot of eighty balls was oxidized for rolling contact fatigue testing.

The Rolling Contact Fatigue testing was performed on four NTN-Bower, ball-on-rod RCF test machines. All tests were performed at a maximum Hertzian contact stress of 786 ksi. Tests were terminated after 600 hours, if a failure had not occurred. Twenty-two RCF tests were performed on non-oxidized balls and twenty RCF tests were performed on oxidized balls. The tests did not meet the prime objective of generating ball failures to allow comparison of oxidized and non-oxidized balls. There were twenty-five rod failures and only one ball failure, in all of the testing.

Acoustic Emission techniques were used to measure the Hertzian contact stress at fracture, for pre-oxidized and non-oxidized ball samples. No significant difference in contact stress at fracture was found between the samples.

3.0 DEVELOPMENT OF THERMAL TREATMENT FOR NBD-200 BEARING BALLS:

Baseline data for the probability of thermal cracking as function of quench temperature difference was developed for Norton Advanced Ceramics Lot #954612, 1/2 in., Grade 5, NBD-200 balls. Ball samples were heated to various temperatures in an inert gas atmosphere and quenched in a heated liquid metal quench bath. Results are shown in Table 1.

Table 1
Baseline Response to Thermal Quenching

Quench Temperature Difference °F (°C)	Number of Balls Tested	Number of Balls Cracked
1100 (611)	50	3
1150 (639)	25	4
1200 (667)	25	8
1250 (694)	25	20
1300 (722)	25	20
1350 (750)	25	22

Ball samples were oxidized in flowing air, at various temperatures and relative humidities, for a fixed one hour treatment time. These samples were thermally quenched using an 1150°F (639°C) temperature differential, using the same techniques as the baseline samples. Table 2 shows the results of this procedure.

Table 2

Response of Oxidized Balls to Thermal Quenching With ΔT of 1150°F (639°C)

Oxidation Temperature °F (°C)	Relative Humidity (%)	Oxidation Time (Minutes)	Quench Temperature Difference °F (°C)	Balls Tested	Balls Cracked
1300(704)	5	60	1150(639)	25	0
1300(704)	50	60	1150(639)	25	0
1500(816)	5	60	1150(639)	25	2
1500(816)	50	60	1150(639)	25	1
1700(927)	5	60	1150(639)	25	1
1700(927)	50	60	1150(639)	25	0

The samples were examined visually. Roughening on one side of the ball surface was noted for all samples. However, the samples treated at 50% relative humidity were noticeably smoother than those treated at 5% relative humidity. There was no observed difference in smoothness at the different oxidation temperatures. The higher oxidation temperature was selected for further study to maximize the effects of the treatment. The thermal quench temperature difference was increased slightly to increase the probability of thermal cracking. Table 3 shows the result obtained at a constant oxidation temperature of 1700°F (927°C), while varying time. From this data, a test time of 30 minutes was fixed for all future trials.

Table 3

Response of Oxidized Balls to Thermal Quenching With ΔT of 1200°F (667°C)

Oxidation Temperature °F (°C)	Relative Humidity (%)	Oxidation Time (Minutes)	Quench Temperature Difference °F (°C)	Balls Tested	Balls Cracked
1700(927)	50	15	1200(667)	25	3
1700(927)	50	30	1200(667)	25	2
1700(927)	50	60	1200(667)	25	3

With the oxidation conditions now fixed at 1700°F (927°C), 30 minutes time, at 50%

relative humidity, data for the probability of thermal cracking as function of quench temperature difference was developed. Results are shown in Table 4.

Table 4
Response of Oxidized Balls to Thermal Quenching With Varying ΔT

Oxidation Temperature °F (°C)	Relative Humidity (%)	Oxidation Time (Minutes)	Quench Temperature Difference °F (°C)	Balls Tested	Balls Cracked
1700(927)	50	30	1150(639)	50	1
1700(927)	50	30	1200(667)	25	3
1700(927)	50	30	1250(694)	25	9
1700(927)	50	30	1300(722)	25	6

A Weibull plot comparing the baseline result to the "optimum" oxidation treatment result is shown in Figure 1. At higher quench temperature differences, there is a plateau in the data. The oxidized balls are more resistant to thermal cracking than the non-oxidized balls. Eighty oxidized balls were prepared for RCF testing and other analyses using the "optimum" oxidation treatment.

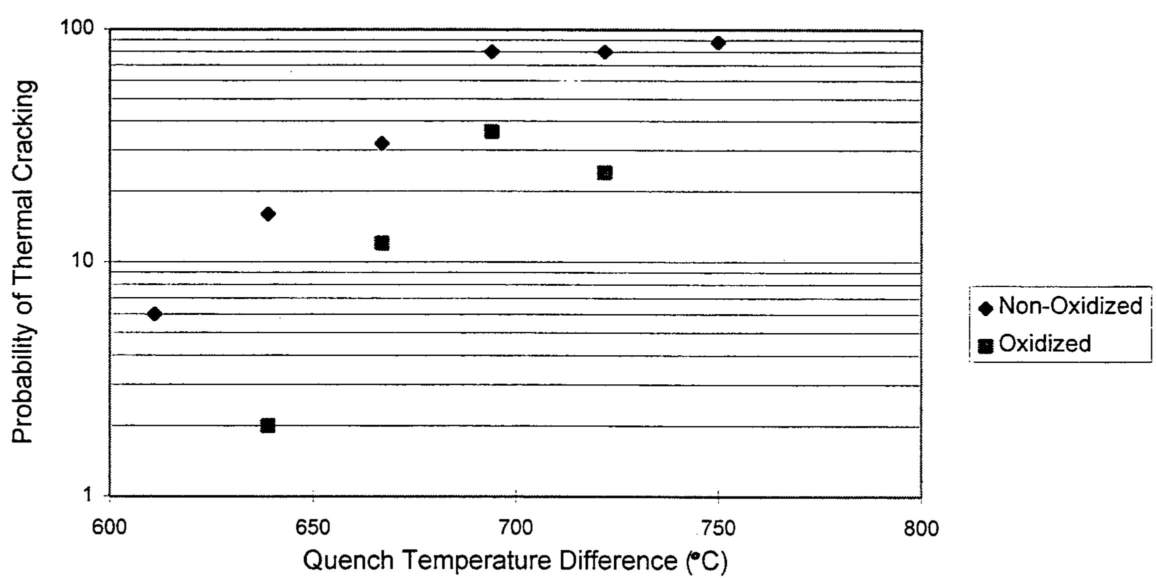

Figure 1 Weibull comparison: oxidized vs non-oxidized balls.

4.0 ANALYSIS OF OXIDIZED BALLS

Auger Energy Spectroscopy (AES) was used to estimate the thicknesses of the oxide layer on the balls oxidized at 1700°F(927°C). The thickness of the surface oxides were determined from the points on the AES sputtering profiles where the oxygen and nitrogen signals intersect. The oxide layer was determined to be only about 100 μin.(2.5μ) thick. The thickness of the oxide layer is a definite limitation if the oxidation technique were to be performed prior to final ball finishing.

Results of dimensional characterization of the oxidized and non-oxidized balls are summarized in Table 5. The oxidation treatment caused deterioration in both surface finish and roundness. Typical limits for silicon nitride bearing balls are 5μin.(1.25μ) roundness and .25$R_a\mu$in.(.006μ) surface finish.

Table 5
Dimensional Characteristics, Oxidized and Non-Oxidized Balls

SAMPLE SIZE	**CHARACTERISTIC**		**NON-OXIDIZED BALLS**	**OXIDIZED BALLS**
30	Lot Mean Diameter, in.(mm)		.499983 (12.69957)	.499999 (12.69997)
	Lot Diameter Variation, in.(μ)		.000003 (.075)	.000005 (.120)
	Ball Diameter Variation, in.(μ)		.000003 (.075)	.000004 (.010)
5	Average Surface Finish $\pm 3\sigma$ R_a μin.(nm)	smooth area	.14$\pm$.03 (3.5$\pm$.75)	.32$\pm$.31 (8.0$\pm$7.8)
		rough area	N/A	1.75$\pm$1.52 (43.8$\pm$38.0)
	Average Roundness$\pm 3\sigma$ μin.(nm)		1.94$\pm$1.71 (48.5$\pm$42.8)	4.54$\pm$6.15 (113.5$\pm$153.8

Sample balls were also loaded in Hertzian contact until failure by cracking was detected by an Acoustic Emission System. After testing, a stereo microscope was used to determine that C-cracks had been formed at the contact zone. Table 6 shows the results of testing oxidized and non-oxidized balls, six balls each, with five cracking trials on each ball. There is no significant difference in contact stress to initiate cracking between the two lots.

Table 6
Results of Ball on Ball Contact Tests

LOT	AVERAGE CRACKING LOAD $\pm 3\sigma$ Lb.(KG)	AVERAGE CONTACT STRESS $\pm 3\sigma$ KSI(GPa)
NON-OXIDIZED	1349.3 ± 118.3 (613.3 ± 53.8)	2599.9 ± 76.9 (17.93 ± 0.53)
OXIDIZED	1406.7 ± 105.8 (639.4 ± 48.1)	2637.6 ± 66.7 ($18.19 \pm .46$)

5.0 ROLLING CONTACT FATIGUE TESTS

5.1. INTRODUCTION

The main objective was to investigate the premise that pre-oxidization of silicon nitride balls improves their fatigue life under rolling contact conditions. The investigation was carried out using NTN-Bower, ball-on-rod, rolling contact fatigue (RCF) test machines. In these machines, three balls are loaded radially against the surface of a rotating rod. The machines are primarily designed to investigate the fatigue life of the rod which experiences four times the number of stress cycles that a ball experiences over the same period of time. To produce more ball failures than rod failures, the test rods used were made from nitrided M50 NIL, which has been shown to have a very high RCF life. The silicon nitride balls used in the tests were NBD-200, manufactured and finished by Norton Advanced Ceramics. The oxidized balls were produced from the manufacturing lot of balls at University of Dayton Research Institute. The rods were produced by The Torrington Company.

Twenty-two RCF tests were performed, using non-oxidized balls, and the results are presented in Section 5.2. Twenty RCF tests were carried out using pre-oxidized balls and these results are presented in Section 5.3. All the tests were carried out at a maximum Hertzian contact stress of 786 ksi(5.42GPa) and using MIL-L-23699 oil as the drip lubricant. To limit the overall test time, tests were terminated after 600 hours, if a failure had not occurred.

5.2. RCF TESTS USING NON-OXIDIZED BALLS

Of the twenty-two RCF tests performed, eleven were terminated manually after completing a minimum of 600 hours without failure. Ten tests were terminated by rod failures, and only one test was terminated by a ball failure. The RCF test results are summarized in Table 7.

Table 7
RCF Test Data for Nitrided M50 NIL Rods With Grade 5 NDB-200 Balls
Maximum Hertizian Contact Stress=786 Ksi (117 lb. Total Spring Force)

Rod ID	Track No. *	Start Date	Start Hours	End Hours	Test Hours	Life cycles x 10^6	Comments
N1	1	10/04/95	9590.0	10211.9	621.9		No Failure. Manual Stop.
	2	10/30/95	211.9	822.0	610.1		No Failure. Manual Stop.
	3	11/29/95	822.0	1447.2	625.2		No Failure. Manual Stop.
	4	12/27/95	1447.2	1725.8	278.6	143.76	Spall on Rod.
	5	01/22/96	1725.8	2390.9	665.1		No Failure. Manual Stop.
N2	1	10/04/95	9951.0	10573.4	622.4		No Failure. Manual Stop.
	2	10/30/95	573.4	975.6	402.2	207.55	Spall on Rod.
	3	11/29/95	975.6	1600.2	624.6		No Failure. Manual Stop.
	4	12/27/95	1600.2	2218.9	618.7		No Failure. Manual Stop.
	5	01/22/96	2218.9	2884.0	665.1		No Failure. Manual Stop.
N3	1	10/04/95	6208.7	6787.1	578.4	298.47	Spall on Rod.
	2	10/30/95	6787.1	7451.6	664.5		No Failure. Manual Stop.
	3	11/29/95	7451.6	8051.8	600.2		No Failure. Manual Stop.
	4	12/27/95	8051.8	8258.2	206.4	106.51	Spall on Rod.
	5	01/22/96	8258.2	8293.2	35.0	18.06	Spall on Rod.
N4	1	10/04/95	8599.5	8668.6	69.1	8.91	Spall on Ball.
	2	10/30/95	8668.6	8984.9	316.3	163.22	Spall on Rod.
	3	11/29/95	8984.9	9029.9	45.0	23.22	Spall on Rod.
N5	1	12/01/95	9029.9	9053.3	23.4	12.08	Spall on Rod.
	2	12/07/95	9053.3	9293.5	240.2	123.95	Spall on Rod.
	3	12/27/95	9293.5	9911.6	618.1		No Failure. Manual Stop.
	4	01/22/96	9911.6	10144.4	232.8	120.13	Spall on Rod.

*see Figure 2

The rods and balls were examined by microscope following the RCF tests. Figure 2 shows the Test Track Identification system used in these tests. The wear tracks on the rods were mainly very faint with no clear width. The rod tracks were clearly defined and measurable in only three cases. There were no visible tracks on the balls used in the tests. Overall, the microscopic examination revealed no significant wear of the rods or balls.

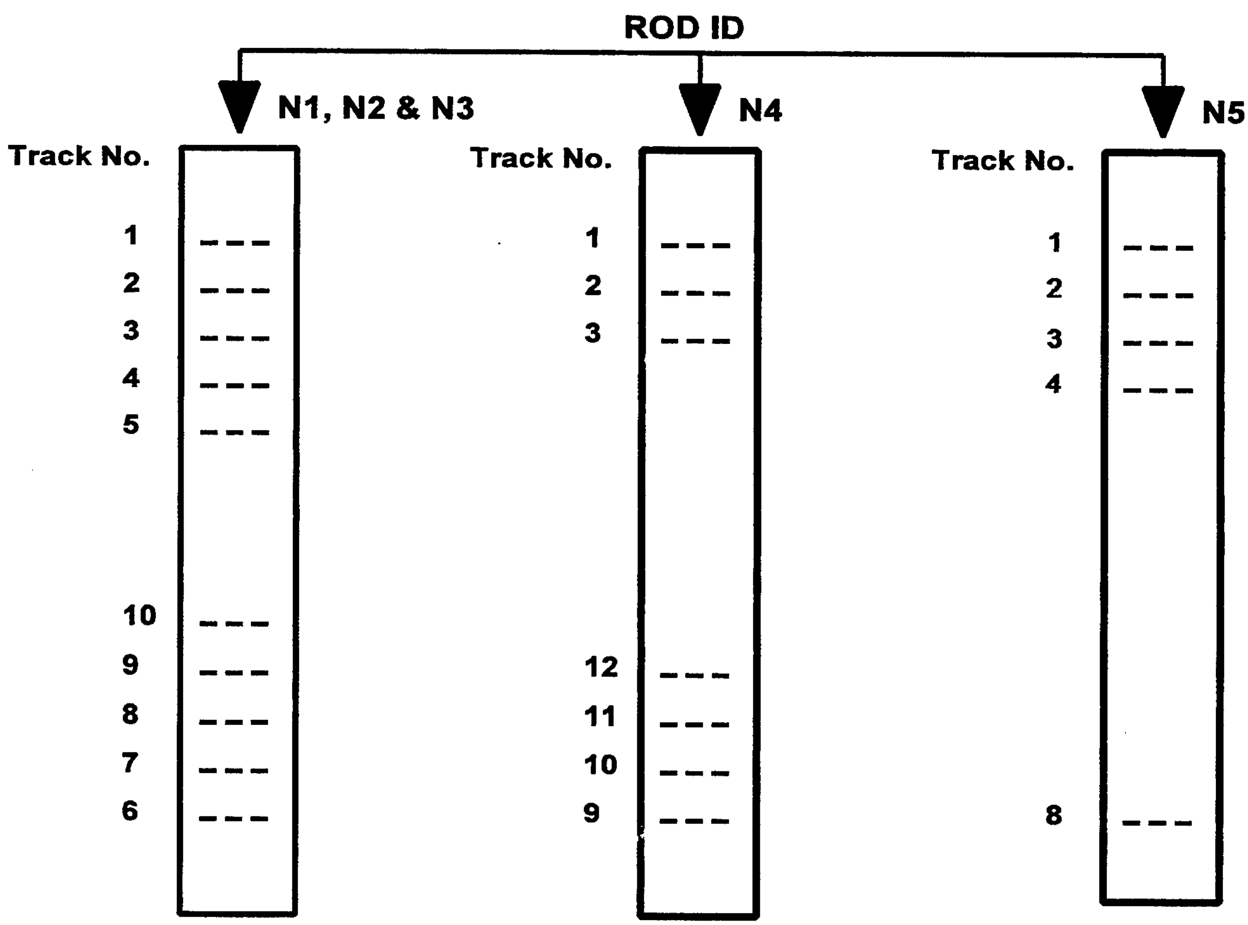

Figure 2 Test track identification.

The results of the microscopic examination are summarized in Table 8. The balls supplied by Norton Advanced Ceramics were not individually identified, but at the completion of each test, the balls were placed in individual plastic bags and labeled with an identification number and information relating them to specific tests. These are the ball identification numbers referred to in Table 8.

Table 8
Widths of Tracks on Rods and Balls from Tests Described in Table 7
(VF) - Very Faint (NVT) - No Visible Track
(s) - spall (p) - partial track

Rod ID	Track No. *	Rod Track Width (mil)	Ball No.	Ball Track Width (mil)	Ball No.	Ball Track Width (mil)	Ball No.	Ball Track Width (mil)
N1	1	VF	1	NVT	2	NVT	3	NVT
	2	VF	13	NVT	14	NVT	15	NVT
	3	VF	25	NVT	26	NVT	27	NVT
	4	VF (s)	43	NVT	44	NVT	45	NVT
	5	VF	55	NVT	56	NVT	57	NVT
N2	1	VF	4	NVT	5	NVT	6	NVT
	2	NVT (s)	16	NVT	17	NVT	18	NVT
	3	VF	28	NVT	29	NVT	30	NVT
	4	VF	46	NVT	47	NVT	48	NVT
	5	VF	58	NVT	59	NVT	60	NVT
N3	1	30 (s)	7	NVT	8	NVT	9	26 (p)
	2	20	19	NVT	20	NVT	21	NVT
	3	VF	31	NVT	32	NVT	33	NVT
	4	VF (s)	49	NVT	50	NVT	51	NVT
	5	VF (s)	61	NVT	62	NVT	63	NVT
N4	1	VF	10	NVT	11	NVT	12	NVT (s)
	2	25 (s)	22	NVT	23	NVT	24	NVT
	3	VF (s)	34	NVT	35	NVT	36	NVT
N5	1	VF (s)	37	NVT	38	NVT	39	NVT
	2	VF (s)	40	NVT	41	NVT	42	NVT
	3	VF	52	NVT	53	NVT	54	NVT
	4	VF (s)	64	NVT	65	NVT	66	NVT

*see Figure 2

5.3 RCF TESTS USING PRE-OXIDIZED BALLS

Of the twenty RCF tests performed, three were terminated manually after completing a minimum of 600 hours without failure, two were terminated by rod wear (no fatigue failure) and the remainder were terminated by rod failures. There were no ball failures. The test results are summarized in Table 9.

Table 9
RCF Test Data for Nitrided M50 NIL Rods With Grade 5 NDB-200 Balls Finished by Norton Advanced Ceramics and Then Oxidized.
Maximum Hertizian Contact Stress=786 Ksi (117 lb total spring force)

Rod ID	Track No. *	Start Date	Start Hours	End Hours	Test Hours	Life cycles x 10^6	Comments
N1	6	04/26/96	2390.9	3037.5	646.6		No Failure. Manual Stop.
	7	05/24/96	3037.5	3231.4	193.9	100.06	Spall on Rod.
	8	06/03/96	3238.7	3344.6	105.9	54.65	Spall on Rod.
	9	07/02/96	8397.5	8440.0	42.5	21.93	Spall on Rod.
	10	07/26/96	607.6	643.7	36.1	18.63	Spall on Rod.
N2	6	04/26/96	2884.0	3067.2	183.2	94.54	Spall on Rod.
	7	05/24/96	3067.2	3238.7	171.5	88.50	Spall on Rod.
	8	06/03/96	8370.4	8397.5	27.1	13.98	Spall on Rod.
	9	07/02/96	580.0	607.6	27.6	14.24	Spall on Rod.
	10	07/26/96	4416.8	5038.7	621.9		No Failure. Manual Stop.
N3	6	04/26/96	8293.2	8332.3	39.1	20.18	Spall on Rod.
	7	05/24/96	8332.3	8370.4	38.1	19.66	Spall on Rod.
	8	06/03/96	538.4	580.0	41.6	21.47	Spall on Rod.
	9	07/02/96	3880.2	4416.8	536.6		No Failure. Rod Wear.
	10	07/26/96	3375.5	3409.3	33.8	17.44	Spall on Rod.
N4	9	05/24/96	467.2	538.4	71.2	36.74	Spall on Rod.
	10	06/03/96	3231.4	3880.2	648.8		No Failure, Manual Stop.
	11	07/02/96	3344.6	3375.5	30.9	15.95	Spall on Rod.
	12	07/26/96	8440.0	8481.8	41.8	21.57	Spall on Rod.
N5	8	04/26/96	144.4	467.2	322.8		No Failure. Rod Wear.

*see Figure 2

The results of post-test microscopic examination of the balls and rods are summarized in Table 10. At the completion of each test, the balls were placed in individual plastic bags and labeled with an identification number and other information relating them to the specific test. These are the numbers referred to in Table 10.

Table 10
Widths of Tracks on Rods and Balls from Tests Described in Table 9
(NVDT) - No Visible Track (s) - spall (p) - partial track
(++) - No identifiable track but change in general surface finish

Rod ID	Track No. *	Rod Track Width (mil)	Ball No.	Ball Track Width (mil)	Ball No.	Ball Track Width (mil)	Ball No.	Ball Track Width (mil)
N1	6	43	1	NVT	2	NVT	3	NVT
	7	NVT (s)	13	NVT	14	NVT	15	NVT
	8	NVT (s)	28	NVT	29	NVT	30	NVT
	9	15 (s)	43	NVT	44	NVT	45	NVT
	10	20 (s)	58	NVT	59	NVT	60	NVT
N2	6	30 (s)	4	NVT	5	NVT	6	NVT
	7	30 (s)	16	NVT	17	NVT	18	NVT
	8	20 (s)	31	NVT	32	NVT	33	NVT
	9	30 (s)	46	NVT	47	NVT	48	NVT
	10	30	49	NVT	50	NVT	51	NVT
N3	6	15 (s)	7	NVT	8	NVT	9	NVT
	7	20 (s)	19	NVT	20	NVT	21	NVT
	8	20 (s)	34	NVT	35	NVT	36	NVT
	9	39	37	NVT	38	NVT	39	NVT
	10	20 (s)	52	NVT	53	NVT	54	NVT
N4	9	25 (s)	22	NVT	23	NVT	24	NVT
	10	NVT	25	NVT	26	NVT	27	NVT
	11	NVT (s)	40	NVT	41	NVT	42	NVT
	12	NVT (s)	55	NVT	56	NVT	57	NVT
N5	8	70 - 100	10	++	11	++	12	++

*see Figure 2

Examination of the rods showed that there were four tests in which the balls left no visible track on the rod even though the rod had spalled. For the majority of the tests, there were visible and measurable tracks on the rods. In the case of track 8 on rod N5, there was major wear, with a track width of .070-.100in.(1.75-2.50mm). The rod had turned blue from heat and was not used for any subsequent tests. In two other cases (track 1 on rod N1 and track 9 on rod N3), the tests were terminated manually, but the track widths were greater than the theoretical Hertzian contact width of .027in.(.67mm), indicating significant rod wear. On the balls used in tests on rods N1, N2, N3 and N4, there were no visible tracks or surface damage. The balls used in the test on rod N5 also showed no defined tracks, but there was a general change in the appearance of the ball surfaces indicating some degree of overall damage.

Pre-test visual inspection of the oxidized balls showed that they all had an unusual surface appearance. For each ball, an area of the surface had a shiny appearance similar to that of non-oxidized balls while the remainder of the surface had a more matt appearance. There was a strong indication that the oxidizing process used had a non-uniform effect on the surfaces of the balls. This could have influenced the RCF test results.

5.4 DISCUSSION

The tests did not meet the prime objective of generating mainly ball failures to allow comparison of the fatigue lives of oxidized and non-oxidized NBD-200 balls. With the non-oxidized balls, only one out of twenty-two tests was terminated by a ball failure. With the oxidized balls, there were no ball failures in the twenty tests.

While the test data do not provide a basis for comparing the fatigue lives of the oxidized and non-oxidized balls, it is possible to compare the fatigue lives of the rods with the different balls. Figures 3 and 4 show the Weibull plots for the rod failures with non-oxidized and oxidized balls respectively.

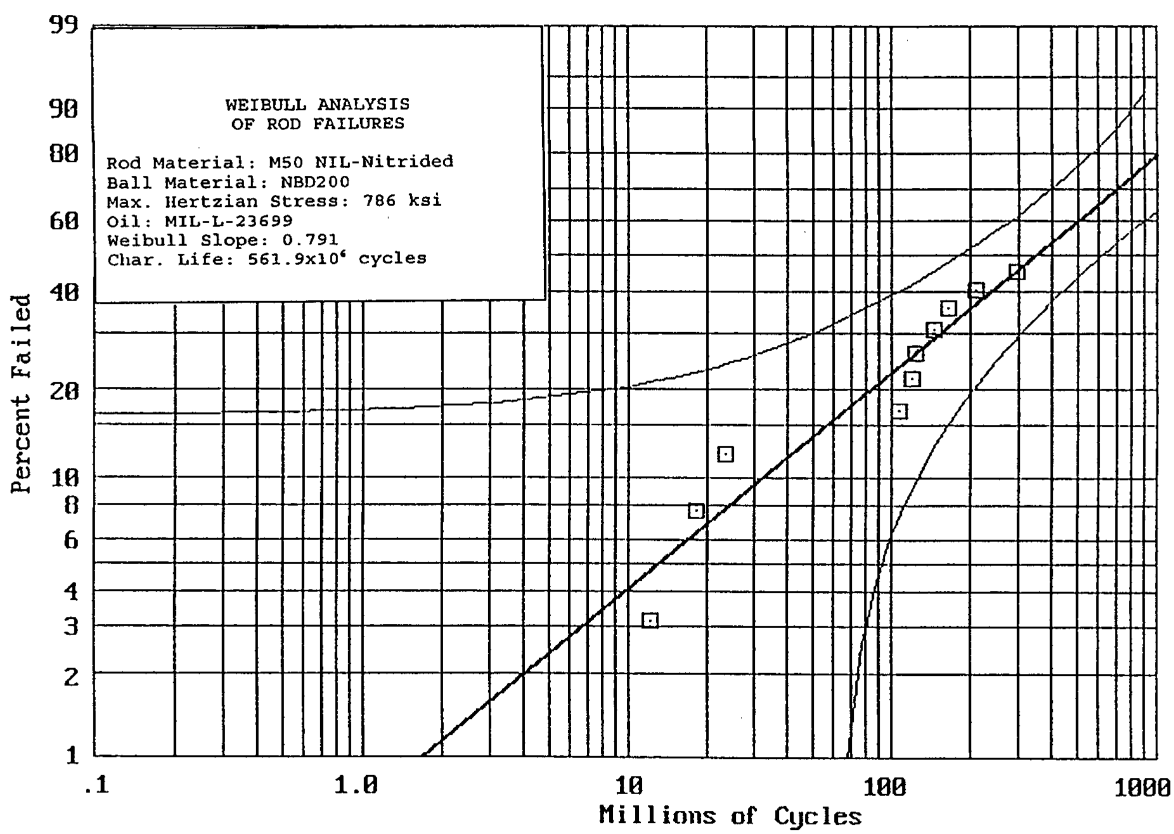

Figure 3 Weibull analysis of rod failures, 561.9 million cycles.

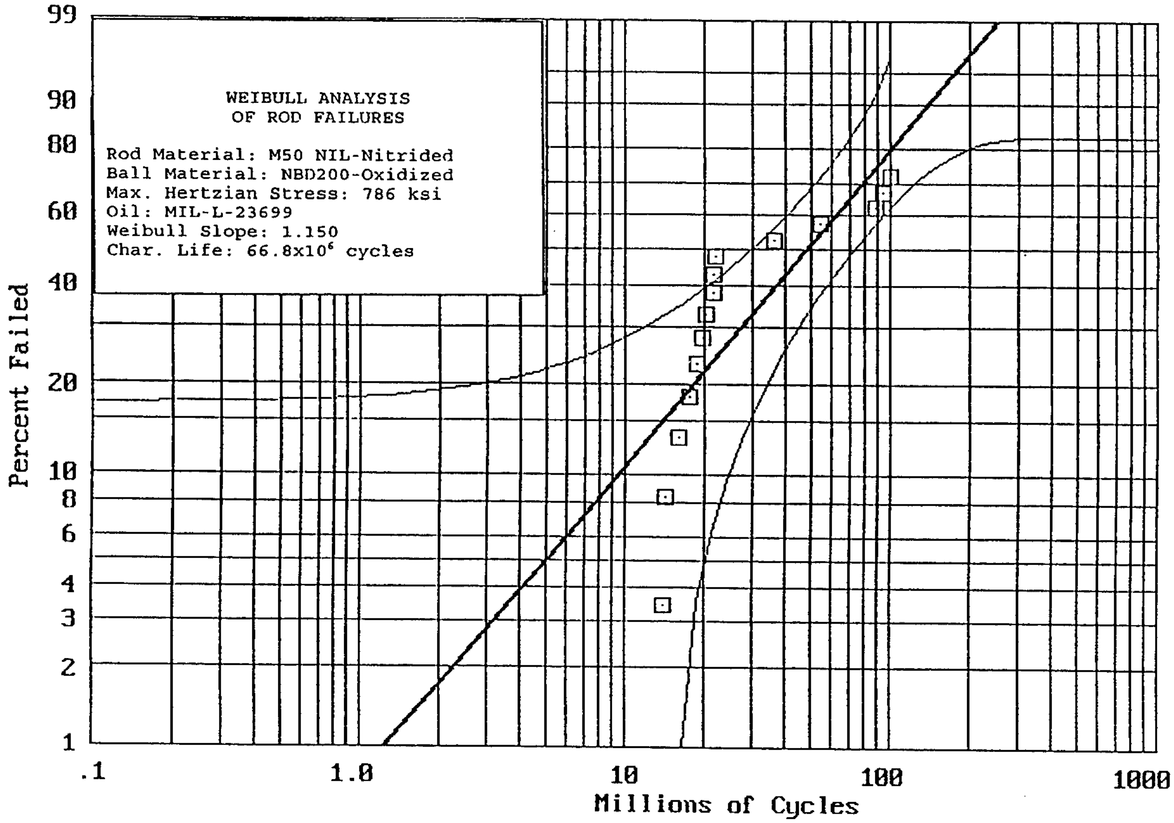

Figure 4 Weibull analysis of rod failures, 66.8 million cycles.

There are distinct differences between the two sets of data. With the non-oxidized balls, the rod B_{10} life was approximately $30x10^6$ cycles, but with the oxidized balls it was only $10x10^6$ cycles. The Weibull slopes of 0.791 (non-oxidized) and 1.15 (oxidized) both indicate a random type of failure. With the non-oxidized balls, seven of the ten rod failures were in excess of $100x10^6$ cycles; whereas, with the oxidized balls, none of the fifteen rod failures exceeded that value. Overall, the life of the nitrided M50 NIL rods was lower with the oxidized balls.

The data with the oxidized balls, Figure 4, give poor correlation to the Weibull line and it appears that there might be two different failure modes involved. There is a group of ten failures over a narrow range of 13.98 - $21.93x10^6$ cycles, while the other five failures appear to be out of line with the first group. Figure 5 shows the results of a Weibull analysis of the first ten failures.

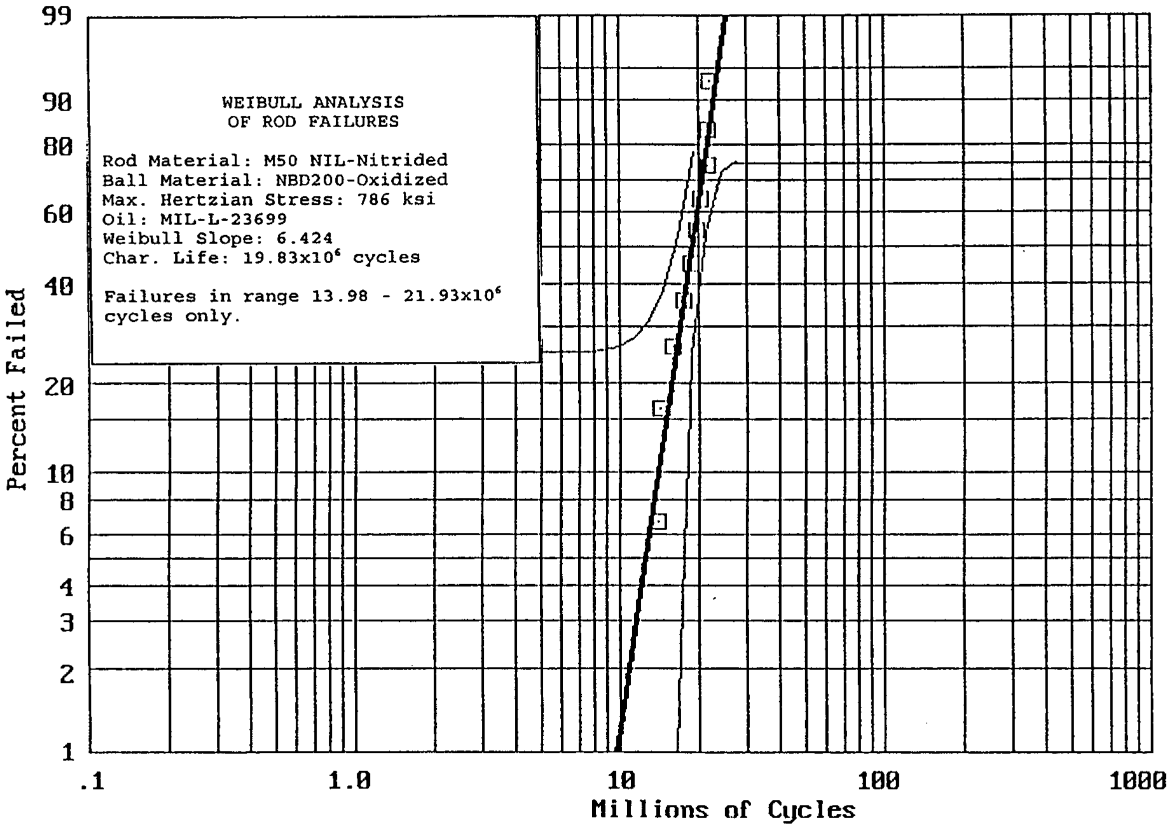

Figure 5 Weibull analysis of rod failures, 13.98 - 21.93 million cycle range.

The data show very good correlation to the Weibull line, which has a high slope of 6.424. The results of a Weibull analysis of the other five failures is shown in Figure 6. Again, the data correlate well with the line but the slope is lower at 2.303. Based on the analyses of the two groups of data, there is reason to believe that there are two different processes leading to failure of the rods. Inspection of the spalls on the rods does not show any significant differences between the two groups of failures. The test heads were all calibrated prior to each test and adjusted to give the same nominal Hertzian stress so this should not have influenced the failures. This would appear to leave two possibilities; inconsistency of the rod material possibly from the nitriding process or inconsistency of the ball material possibly from the oxidizing process. If the phenomenon was the result of inconsistent rod material, one would expect to see a similar pattern in the rod failures generated with the non-oxidized balls, since the tests were carried out on the same rods.

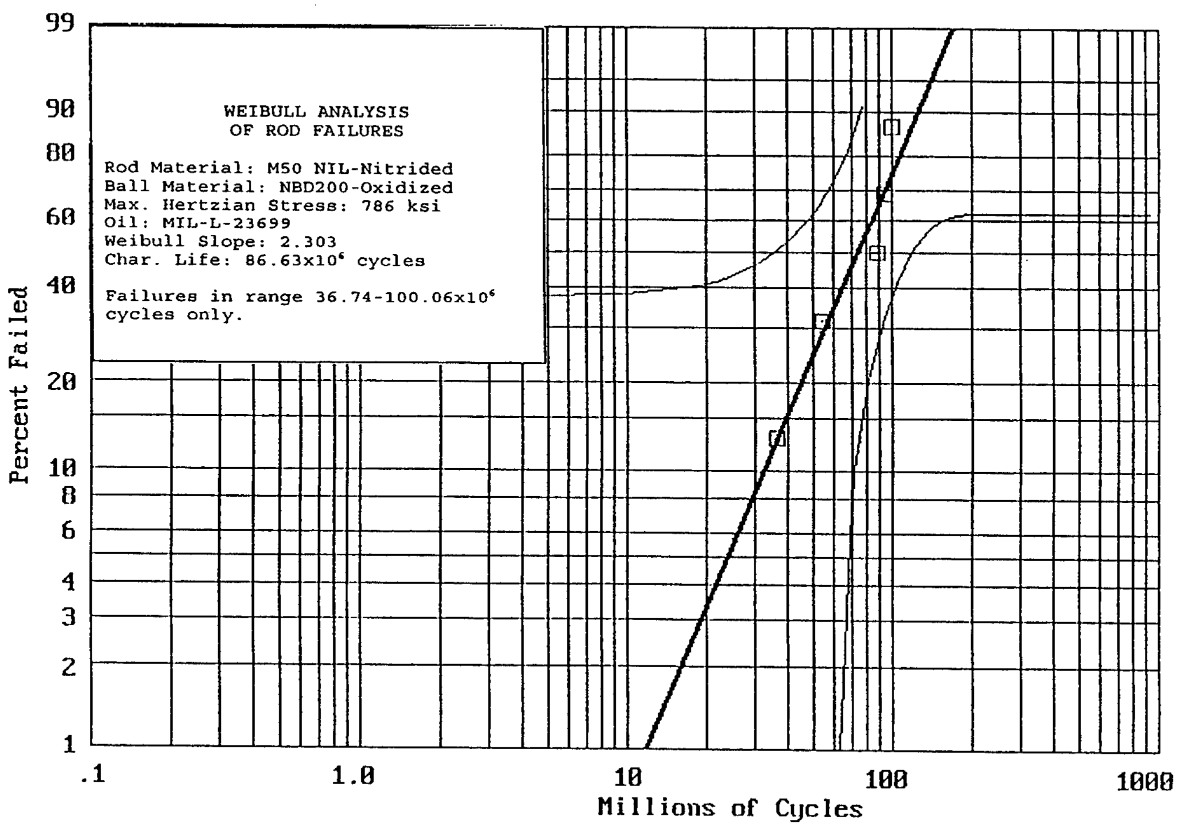

Figure 6 Weibull analysis of rod failures, 36.74 - 100.06 million cycle range.

Referring back to Figure 3, there appears to be two groups of data with the non-oxidized balls. Three failures occurred in the 10 - 30x10^6 cycle range while the other seven failures were in excess of 100x10^6 cycles.

Figure 7 shows the results of a Weibull analysis of the three early failures.

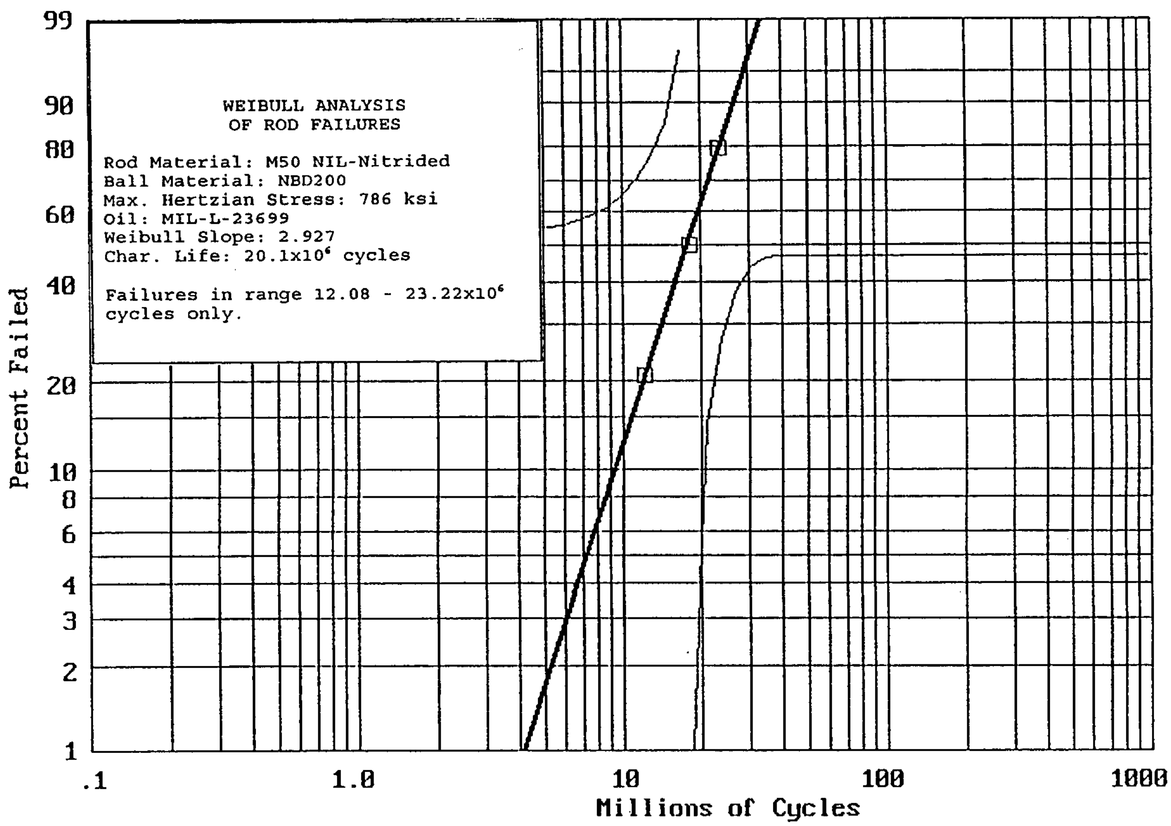

Figure 7 Weibull analysis of rod failures, 12.08 - 23.22 million cycle range.

Comparing this to the "equivalent" data with the oxidized balls (Figure 5), the line for the non-oxidized balls falls within the 90% confidence band of the line for the oxidized balls. This suggests that, at the 90% confidence level, there is no significant difference in the early rod failures generated with oxidized and non-oxidized balls.

The result of Weibull analysis of the seven higher failures with non-oxidized balls is shown in Figure 8. Comparing this with the equivalent data for the oxidized balls shown in Figure 6, the two lines have a similar slope, but the rod life with the non-oxidized balls is at least twice that with the oxidized balls.

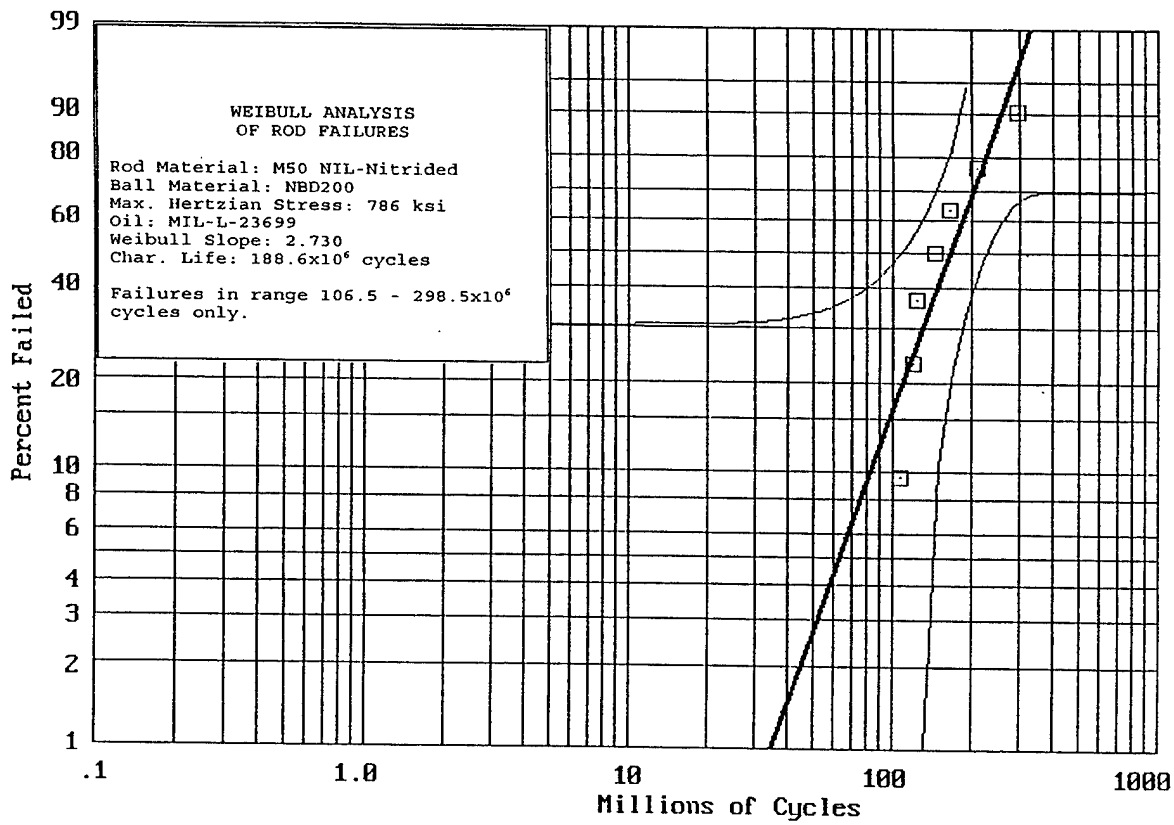

Figure 8 Weibull analysis of rod failures, 106.5 - 298.5 million cycle range.

Overall, it appears that the rod failure data could have been influenced by inconsistency in the rod material, and that the oxidized balls gave shorter rod life.

6.0 RESULTS

The oxidation treatment developed for NBD-200 silicon nitride balls did not improve the RCF life of the balls. The oxidation treatment caused ball surface and geometry degradation. Excessive rod wear was observed in some RCF tests with oxidized balls. Overall, the life of the M-50 NIL rods was shorter with the oxidized balls. For non-oxidized balls, only one ball failure occurred in all testing.

7.0 CONCLUSIONS

Oxidation treatment does not appear to be a useful technique for improving the reliability of NBD-200 silicon nitride bearing balls. RCF testing of NBD-200 silicon nitride bearing balls with nitrided M-50 Nil rods does not produce a significant percentage of ball failures. Alternative methods, such as four ball fatigue testing, or hybrid bearing fatigue testing, should be considered for future work.