THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

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Report No 404

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D Saynor, B.Sc.

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SUMMARY

The effect of shot peening exposure time on the fatigue life of cold drawn carbon and prehardened and tempered chrome vanadium spring materials has been studied for batch type shot peening. The work indicates that the most common method for determining optimum exposure times currently used (based on demanding military specifications) leads to excessive periods which do not produce optimum fatigue performance in springs. In fact very short exposure times have been shown to give significant improvements in fatigue performance indicating that fears of underpeening (insufficient coverage) may have been previously exaggerated.

These findings are of considerable significance and the report therefore recommends more exhaustive further work to investigate this phenomenon in more detail.

CONTENTS

THE INFLUENCE OF SHOT PEENING EXPOSURE TIME ON THE FATIGUE LIFE OF BATCH PEENED HELICAL COMPRESSION SPRINGS

1. INTRODUCTION

Shot peening is a vitally important process in the production of springs which must survive highly stressed fatigue conditions in service. The improvement in life which can be achieved by the correct application of shot peening is dramatic and spring designers rely heavily upon this improvement when selecting safe operating stresses.

Despite this critical role, the details of the shot peening process are not well understood. However, a good understanding of the major features of the process is essential if the process is to be optimised and controlled to provide the maximum fatigue life after shot peening.

In the past, SRAMA has reported on work which has investigated the effect of shot size and shot velocity on the fatigue life of springs (1 and 2). However, one of the major variables - exposure time - has not been considered to date.

The effect of exposure time can be anticipated to be significant. The amount of time for which each spring is exposed to the direct blast of shot will determine the number of impacts made by the shot on the surface of the spring (known as coverage). This in turn will determine the level of beneficial compressive stress produced in the outer layers of the wire which will have a direct bearing upon the fatigue life of the shot peened spring.

It can be expected therefore that insufficient exposure to the blast (low coverage or underpeening) will result in relatively low fatgiue life. On the other hand, long exposures will result in overpeening with further impacts being superimposed upon previous shot impacts. This can cause surface lapping, generating stress raisers which reduce the fatigue life of the spring.

There exists therefore an optimum exposure time which will maximise fatigue life by ensuring sufficient coverage to avoid underpeening but not so much as to run the risk of overpeening. This optimum time will be dependent upon many factors within the shot peening process:-

1. Size, type and quality of shot used.
2. Shot velocity and flow rate.
3. Orientation of shot blast and springs within machine.
4. Batch size of springs within machine (for batch type peening machines).

All these factors are controlled by the Almen arc test, and the optimum exposure time is related to a condition termed saturation in the Almen test. Saturation is defined as being achieved at an exposure time (T_1) such that a doubling of the exposure time (to $2T_1$) causes less than a fixed percentage rise in Almen arc height (see Fig 1). Different national and in-house standards on shot peening give different values for the fixed percentage rise allowed. This leads to different optimum saturation times being established when working to different standards.

For example the SAE manual on shot peening (3) recommends a 20% increase in arc height as being acceptable. The US defence specification (4) stipulates 10%, as does the British military specification (5). Several in-house specifications (6,7,8) have also been surveyed and the most common arc rise increase is 10%. As a consequence of this predominance of 10% the draft British standard for shot peening springs (9) also specifies a 10% increase as the basis of saturation determination.

From Fig 1 it can be seen that the use of a low percentage arc rise increase (10% as opposed to 20%) leads to a considerable increase in the exposure time for the shot peening process. This presumably is to ensure that underpeening is avoided at all costs. However, using such extended exposure times could lead to a serious overpeening condition.

The selection of arc rise increases of 10% or 20% seems arbitrary. There is no documented experimental evidence to support or disprove either. For this reason SRAMA undertook this work to establish optimum exposure times based on spring fatigue data.

2. TEST METHOD

Batches of identical compression springs were exposed for different exposure times under identical shot peening conditions. All springs were stress relieved after peening and then fatigue tested under identical conditions to failure or to 2,000,000 cycles. The performance of each batch was then analysed using the Weibull technique (10,11) to establish statistical confidence in any differences in fatigue life for each batch.

Since the optimum exposure time might differ for different spring materials the tests were conducted on patented cold drawn carbon steel material and prehardened and tempered chrome vanadium materials as being the most common material types used for shot peened springs.

3. SPRING DESIGNS

The two spring designs used are listed in Table I. Both designs have a relatively high solid stress and were fully prestressed prior to testing.

4. SHOT PEENING CONDITIONS

All the springs were shot peened in a Tilghman Wheelabrator WTBOA batch type machine. The shot used was conditioned cut wire S330, the impellor speed was 2,750 rpm and the impellor motor current 9 amps. Under these conditions Almen test strips were peened within a representative batch volume of 0.8ft^3 of ballast springs. The strips were removed at different exposure times and the arc height measured. This enabled a very accurate arc height - exposure curve to be plotted - Fig 2.

At each exposure time five blocks were removed and the average arc rise plotted on Fig 2. Table II lists all the measurements and gives an indication in the scatter of the readings.

From this curve it can be seen how the saturation exposure time is highly dependent upon the specified arc height increase. If the 20% increase is used, the saturation exposure time is only 3 minutes. However, if the 10% increase is used the saturation exposure time extends to 25 minutes.

Once the Almen arc rise curve had been produced, the test springs were shot peened. Batches were removed from the shot peener at 3, 6, 10, 16, 25, 35, 50 and 75 minutes with ballast springs being added after each removal to maintain the overall batch volume within the peening chamber.

After peening, all springs were given an identical stress relief of 225°C for 30 minutes.

5. FATIGUE TESTING

All springs were tested at 2780 rpm on the Association's single station fatigue machines. All the cold drawn samples were tested between stress levels of 100 N/mm^2 and 1000 N/mm^2 whilst the chrome vanadium samples were tested between 100 N/mm^2 and 1025 N/mm^2.

All springs were individually load tested to determine the test lengths for setting the fatigue machines to generate the required stress levels.

Cycling was continued until the spring failed, at which point the number of cycles to failure was recorded, or until 2,000,000 cycles was achieved without failure at which point the test was stopped.

The full results for the cold drawn material are given in Table III and for the chrome vanadium material in Table IV.

6. ANALYSIS OF RESULTS

The method used to analyse the fatigue data produced was the Weibull Analysis. The use of this technique has been discussed in a previous SRAMA report (10) in detail.

The analysis allows probabilities of failure to be determined and significant differences between batches to be established when fatigue data exhibit an inherent amount of scatter. By plotting log life against cumulative percentage failure a Weibull plot is generated, which should ideally produce a straight line relationship.

The Weibull plots for the results obtained are shown in Figs 3-20. Taking Fig 4 as an example, it shows that for the cold drawn material subject to a 3 minute peening exposure, 10% of all samples would fail before 340,000 cycles (known as the B_{10} life) whilst 50% of all samples would fail before 850,000 cycles (known as the B_{50} life). The slope of the plot is an indication of the overall scatter in the results. A steep slope indicates little scatter whilst a relatively flat plot indicates considerable scatter in the results.

By comparing B_{10} lives for each exposure time it is possible to rank the fatigue performance; the aim being to maximise the B_{10} life since this indicates the optimum shot peening condition.

7. RESULTS

The rankings of the B_{10} lives for both materials are given below:-

Cold Drawn Carbon			Chrome Vanadium		
Exposure Time	B_{10} Life	Weibull Slope	Exposure Time	B_{10} Life	Weibull Slope
10 min	403,000	2.08	3 min	551,000	1.39
16 min	349,000	4.32	35 min	374,000	2.27
3 min	342,000	2.03	16 min	335,000	2.95
6 min	314,000	3.24	10 min	317,000	1.45
50 min	305,000	4.87	6 min	310,000	2.10
75 min	296,000	6.28	50 min	263,000	2.54
35 min	241,000	2.71	25 min	258,000	2.33
25 min	231,000	2.40	75 min	211,000	2.32
0 min	89,000	6.10	0 min	56,000	6.39

The above rankings must be assessed for significance before firm conclusions can be made on the exposure time effect. Due to the large amount of scatter in fatigue results, improvements in B_{10} life can be due to chance alone rather than being representative of a significant improvement caused by different exposure times.

It is possible to analyse the results obtained to determine with what confidence one can state that a measured improvement in B_{10} life is not due to chance alone. The method is described in detail in the SAE Manual of Leaf Spring Design (11) which considers the scatter in the results (as measured by the Weibull slope), the number of samples and the ratio of the B_{10} lives.

A summary of this analysis is contained in Tables V and VI for the cold drawn carbon and chrome vanadium materials respectively. Taking an example from Table V the B_{10} lives of the 16 and 35 min exposure times are 349,000 and 241,000 cycles respectively. From the Table, given the scatter in results and the number of samples tested we can have 90% confidence that the fatigue life for 16 mins exposure is genuinely superior to the 35 mins exposure (ie there is only 1 in 10 chance that the measured improvement is spurious).

From a detailed consideration of the B_{10} lives it is difficult to establish any definite relationship between fatigue life and exposure time. Definitely all exposure times give a significant improvement in life for both materials when compared with unpeened springs. It is also possible to infer that the shorter exposure times (3, 6, 10, 16 mins) give better performance than the longer periods (25, 35, 50, 75 mins) with the exception of a 35 mins exposure for chrome vanadium material which yields a suprisingly high B_{10} life. However, an examination of the Weibull plot for this situation (Fig 18) reveals that this result may be suspect.

The results on a Weibull plot should in theory lie close to a straight line. This feature is exhibited in practice by all the plots generated in this work with the exception of the 35 mins exposure chrome vanadium material which shows coniderable deviation from a straight line. A numerical value which expresses how closely a set of points lies to a straight line is known as the regression coefficient. If points lie exactly on a line, the regression coefficient is one. For all the plots produced in this work the coefficient lies closely in the range .993 (Fig 7) and .929 (Fig 5) except the plot under scrutiny (Fig 18) which has a regression coefficient of 0.834 - markedly inferior to the remainder. The B_{10} life for this condition must therefore be treated with caution.

The B_{10} life ranking is not the only assessment which can be made of the data. The analysis can be supplemented by considering the number of samples within each batch which survived 2,000,000 cycles without failure. Such an analysis gives an assessment of which exposure time yielded high lives, and leads to the following rankings for each material.

Cold Drawn Carbon		Chrome Vanadium	
Exposure Time	% of Batch Surviving 2.10^6 Cycles	Exposure Time	% of Batch Surviving 2.10^6 Cycles
3 min	55	3 min	60
10 min	50	10 min	35
6 min	25	6 min	30
16 min	15	35 min	30
25 min	10	16 min	15
35 min	0	25 min	15
50 min	0	50 min	5
75 min	0	75 min	5
0 min	0	0 min	0

The ranking provides a more coherent assessment of the effect of exposure time than the B_{10} life analysis. It can clearly be seen that increased exposure above 3 mins yields poorer fatigue performance for both materials. However, a high degree of caution is required with such an assessment, since in reality it is early failures which generate problems in practical applications, and the B_{10} life provides a more useful guide for this than percentage survival at 2,000,000 cyles.

8. DISCUSSION

The combined assessments provided by the B_{10} life and percentage survival rankings provide a detailed and surprising analysis of the effect of shot peening exposure time on the fatigue life of springs. It is clear by examining the results for a 25 min exposure that the most popular basis for determining optimum peening exposure time (ie 10% maximum increase of Almen arc rise for doubled exposure time) leads to an overpeening condition due to the excessive exposure. Consequently the fatigue performance is well below the optimum.

Overall, lower exposure times seem to provide better performance. The effect on early failures (as shown by the B_{10} life analyses) is relatively marginal. However, the effect on longer lives is more dramatic and clear cut with a very short 3 min exposure providing consistently the best performance (over 50% of both batches survived 2,000,000 cycles without failure). If the few low life failures experienced with the 3 min exposure could be removed the overall improvement would be very great.

At this point it is probably worthwhile considering what occurs during batch peening to gain an uderstanding of why this situation occurs. The springs in a batch peening machine (as used in this work) tumble at random beneath a curtain of high velocity shot in an enclosed chamber. Depending upon the batch size and the pattern of the shot curtain, springs will be exposed to different zones of the blast with a random orientation for varying lengths of time. If the overall exposure time for the batch is short (such as 3 mins) there is a high probability that a small proportion of the springs within the batch will not be exposed for sufficient time to receive adequate peening coverage. Such springs under subsequent test yield low lives. However, the bulk of the batch receive the correct coverage and give an average performance much better than the few low life samples.

When long exposure times are used the probability of some of the springs receiving insufficient coverage is dramatically reduced. However, the bulk of the springs receive too much exposure thus reducing the average performance of the batch.

The exposure time selected is therefore a compromise between these two opposing factors. Short 3 mins exposure provides the optimum overall performance but longer exposures remove the early failures which can cause problems. For batch peening in the SRAMA plant an exposure time of 10-16 mins is therefore a pragmatic optimum, representing a saturation condition defined by a 12 $^1/_2$% increase in Almen arc rise.

What is really required however is an improved shot peening process which removes the random nature of the batch process and can take advantage of the great overall improvement in fatigue life to be obtained by short exposure. Such a process does exist and is known as on-line peening.

In the on-line process each spring is treated individually as it passes beneath the shot blast on a conveyor belt. From the results of this work it would appear that on-line peening has considerable potential, provided sufficient control can be exercised to establish the optimum exposure time (determined by the conveyor belt speed). The application of on-line techniques to other than large hot-coiled springs is a relatively new development but is well worth further study based on the findings of this work.

9. CONCLUSIONS

1. Exposure time has a significant effect on the fatigue life of springs produced from both drawn carbon and chrome vanadium materials. It is an important peening variable which must be closely controlled for optimum fatigue life.

2. Normal recommended practice for determining optimum peening conditions based on a 10% maximum increase in Almen arc rise for doubled exposure time leads to an overpeening condition due to extended exposure times. This does not generate optimum fatigue performance in springs.

3. In batch peening, short exposure times in the order of 3 mins give the best average performance but yield a small but significant proportion of early failures due to underpeening as a result of the dynamics of the tumbling action.

4. Long exposure times (above 25 min) lead to significant reduction in average peformance due to overpeening.

5. A compromise exposure time of 10-16 mins is the best for the SRAMA machine operating under normal conditions. This compares with 3 mins based on more demanding MIL and DEF practices (10% Almen arc rise increase).

6. On-line shot peening has potential for achieving the best results from short exposure peening.

10. FURTHER WORK

This work must be repeated to confirm the overall findings which are highly significant. The repeat work should use different analysis techniques which will monitor the effect of exposure time on the fatigue limit (at 10,000,000 cycles) and will provide a more exhaustive and robust statistical analysis of the results - a Probit analysis is recommended (see SRAMA Report 274 (10)).

Included in the work should be a comparison with on-line peening at various conveyor speeds since the potential for controlled optimisation of this process is very great with substantial improvements in fatigue life.

11. REFERENCES

1. SRAMA Report No 217, "An Investigation into the Effect of Shot Size in Shot Peening", G C Bird, September 1973.

2. SRAMA Report No 267, "Shot Peening and the Effect of Shot Size on Spring Performance", G C Bird, November 1976.

3. SAE Manual on Shot Peening, SAE J808a: 1967.

4. Military Specification MIL-S-13165B: 1966, "Shot Peening of Metal Parts".

5. Defence Standard DEF 03-21/Iss 1: 1983 "Mechanical Methods for the Inducement of Compressive Surface Residual Stress".

6. Clayton Dewandre Specification CDS 228: 1985, "Controlled Shot Peening of Steel Springs".

7. Dowty Rotol Specification PS 123 Iss 4: 1982, "Shot Peening".

8. Caterpillar Engineering Specification IE 2054 Iss 4: 1972.

9. Draft British Standard April 1985, "Standard for the Shot Peening of Spring Steel Components".

10. SRAMA Report No 274, "Statistical Analysis of Fatigue Data produced from Compression Springs", J Deforges, May 1977.

11. SAE Manual HS J788: 1982, "Manual on Design and Application of Leaf Springs".

TABLE I SPRING DESIGNS

	Cold Drawn Carbon	Chrome Vanadium
Material Specification	BS 5216 HD3	Oteva 62
Wire Diameter	3.99	3.66 mm
Outside Diameter	26.67	25 mm
Free Length	66 mm	62 mm
Total Coils	8	8
Ends	Closed + Ground	Closed + Ground
LTHT after Coiling	375°C/30 mins	400°C/30 mins

TABLE II ARC HEIGHT MEASUREMENTS

Exposure Time (min)	Almen Arc Rise (in)					Ave AAR (in)
	1	2	3	4	5	
2	9.3	9.1	11.0	6.7	6.1	8.44
3	10.3	9.5	11.4	10.3	10.5	10.40
5	14.4	12.1	13.0	13.1	10.5	12.62
6½	14.3	14.5	12.5	13.5	12.8	13.52
7½	14.5	14.3	12.0	15.1	14.1	14.00
10	14.7	13.5	14.1	14.1	14.2	14.12
13	15.6	14.5	14.3	15.1	15.2	14.94
15	14.6	14.6	17.5	15.3	15.6	15.52
20	15.9	16.4	16.5	17.1	16.3	16.44
25	16.3	17.5	16.3	16.7	15.5	16.46
30	17.1	16.5	16.6	17.1	18.0	17.06
40	18.1	18.0	19.0	18.6	18.5	18.44
50	19.1	19.1	18.5	19.2	17.6	18.70
56	18.7	18.5	18.7	18.1	18.6	18.52

TABLE III FATIGUE RESULTS - COLD DRAWN CARBON MATERIAL

Exposure Time (mins)								
0	3	6	10	16	25	35	50	75
78,250	227,300	287,020	263,820	266,740	130,030	186,050	252,840	257,720
87,250	316,460	300,840	372,830	353,980	279,450	205,050	288,590	279,800
91,060	414,090	310,780	444,000	368,520	293,760	235,090	336,020	321,190
95,050	422,540	344,010	471,010	400,730	304,210	339,630	340,620	331,830
103,080	442,900	385,020	576,820	419,030	309,070	349,160	347,030	340,040
107,790	574,000	392,530	709,090	454,710	349,410	362,210	379,660	346,740
109,560	651,330	497,240	826,020	466,350	408,070	378,030	383,320	358,110
112,180	686,490	510,120	851,750	487,530	412,210	397,050	427,120	367,200
119,440	926,600	521,900	921,860	500,790	427,760	455,980	444,850	370,090
120,640	2,000,000*	564,430	1,279,830	542,800	484,160	478,980	444,870	384,440
127,400	"	600,010	2,000,000*	557,870	504,170	492,730	456,210	435,450
147,380	"	688,220	"	643,630	513,200	495,430	463,450	438,990
147,500	"	692,930	"	667,860	531,570	503,950	463,930	440,720
151,190	"	828,370	"	724,860	600,030	523,480	496,490	451,640
155,370	"	876,300	"	849,990	684,160	539,280	571,150	465,010
160,210	"	2,000,000*	"	1,103,360	705,140	551,890	638,820	473,640
163,390	"	"	"	1,691,780	824,210	579,660	664,480	494,620
173,500	"	"	"	2,000,000*	1,010,040	593,280	720,540	563,760
221,290	"	"	"	"	2,000,000*	616,960	829,720	569,990
223,270	"	"	"	"	"	874,020	1,209,770	625,230

* = Spring unbroken at 2,000,000 cycles

TABLE IV FATIGUE RESULTS - CHROME VANADIUM MATERIAL

Exposure Time (Mins)								
0	3	6	10	16	25	35	50	75
48,320	300,480	227,470	217,160	289,930	185,960	305,300	201,095	181,310
51,940	484,710	281,380	231,510	302,830	229,450	394,840	243,980	195,600
57,110	565,740	302,740	360,950	364,560	233,060	482,050	259,160	197,770
64,250	772,580	344,070	420,500	389,060	372,000	486,520	293,230	271,270
66,330	1,013,670	504,320	470,510	400,430	386,130	488,550	399,150	280,740
67,050	1,138,990	551,390	794,670	431,000	426,680	558,870	416,110	284,820
67,370	1,603,710	623,820	839,590	540,850	478,140	567,470	432,660	397,080
69,100	1,802,880	643,390	938,600	541,690	492,200	573,000	485,150	401,070
72,070	2,000,000*	661,910	986,410	635,820	537,150	577,600	516,000	415,420
74,690	"	744,360	1,146,550	653,300	543,490	1,037,970	535,680	493,200
74,770	"	784,020	1,193,860	666,050	558,990	1,038,420	585,150	522,820
77,890	"	1,016,470	1,258,570	709,400	571,010	1,388,360	626,300	525,020
88,610	"	1,167,960	1,535,260	720,760	614,320	1,525,180	629,590	537,890
89,680	"	1,738,720	2,000,000*	807,930	661,210	1,872,780	654,740	617,780
92,800	"	2,000,000*	"	836,500	855,810	2,000,000*	689,740	654,740
95,300	"	"	"	1,195,010	867,890	"	691,380	714,690
105,090	"	"	"	1,399,730	1,599,630	"	720,750	794,600
118,980	"	"	"	2,000,000*	2,000,000*	"	853,030	804,300
126,400	"	"	"	"	"	"	935,150	921,290
204,520	"	"	"	"	"	"	2,000,000*	2,000,000*

* = spring unbroken at 2,000,000 cycles

TABLE V CONFIDENCE NUMBERS FOR COLD DRAWN CARBON MATERIAL

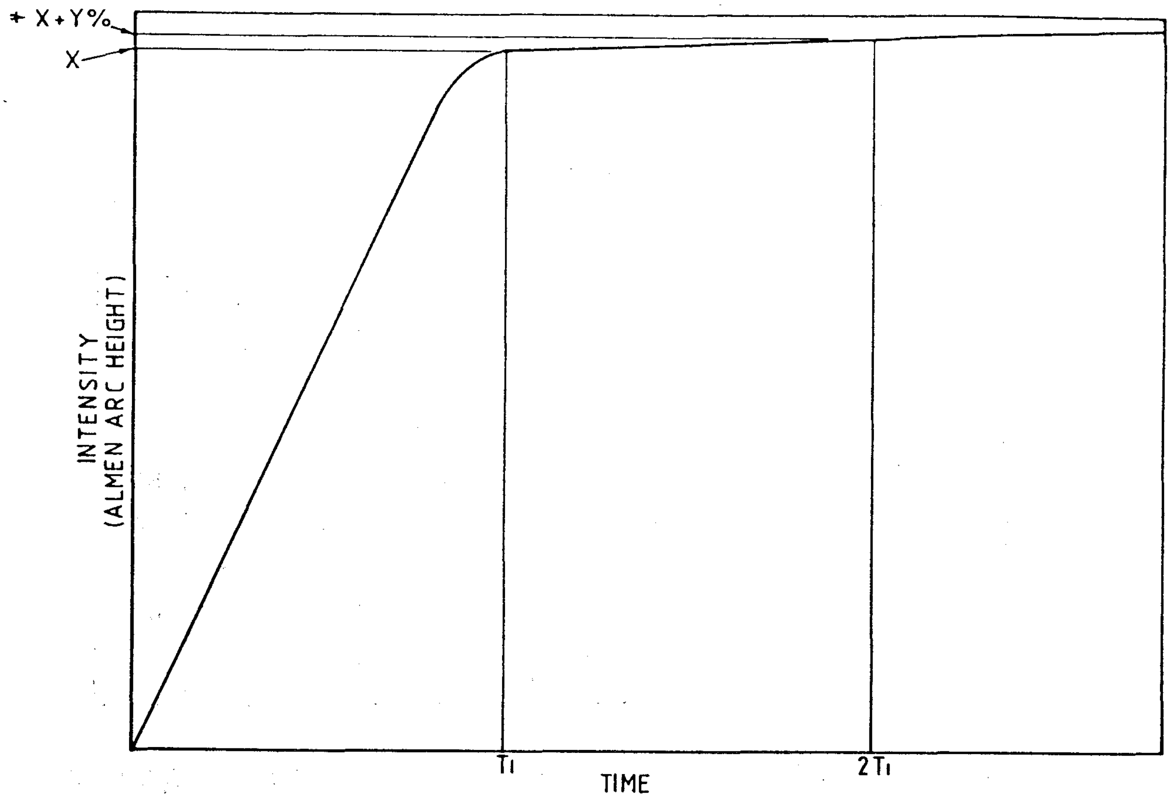
		Exposure Time (min)								
		0	25	35	75	50	6	3	16	10
Exposure Time (min)	0		99	99	99	99	99	99	99	99
	25	—		55	84	84	81	80	90	91
	35	—	—		81	81	78	79	90	90
	75	—	—	—		55	55	70	81	85
	50	—	—	—	—		55	64	73	82
	6	—	—	—	—	—		55	65	74
	3	—	—	—	—	—	—		55	63
	16	—	—	—	—	—	—	—		67
	10	—	—	—	—	—	—	—	—	

TABLE VI CONFIDENCE NUMBERS FOR CHROME VANADIUM MATERIAL

		Exposure Time (min)								
		0	75	25	50	6	10	16	35	3
Exposure Time (min)	0		99	99	99	99	99	99	99	99
	75	—		68	71	79	77	89	92	95
	25	—	—		55	66	64	75	79	91
	50	—	—	—		64	63	74	79	91
	6	—	—	—	—		55	55	66	85
	10	—	—	—	—	—		55	61	79
	16	—	—	—	—	—	—		59	84
	35	—	—	—	—	—	—	—		75
	3	—	—	—	—	—	—	—	—	

Tables of percentage confidence in significant life improvement between exposure times.

(e.g. we are 90% confident that a 16min exposure is significantly superior to a 25min exposure for Cold Drawn Material and 75% for confident of an improvement for Chrome Vanadium Material).



T1 = SATURATION TIME
X = MINIMUM INTENSITY REQUIRED
Y = ALLOWABLE PERCENTAGE INCREASE IN INTENSITY FOR SATURATION CONDITION

FIG 1 : GENERAL ARC RISE CURVE SHOWING SATURATION CONDITION

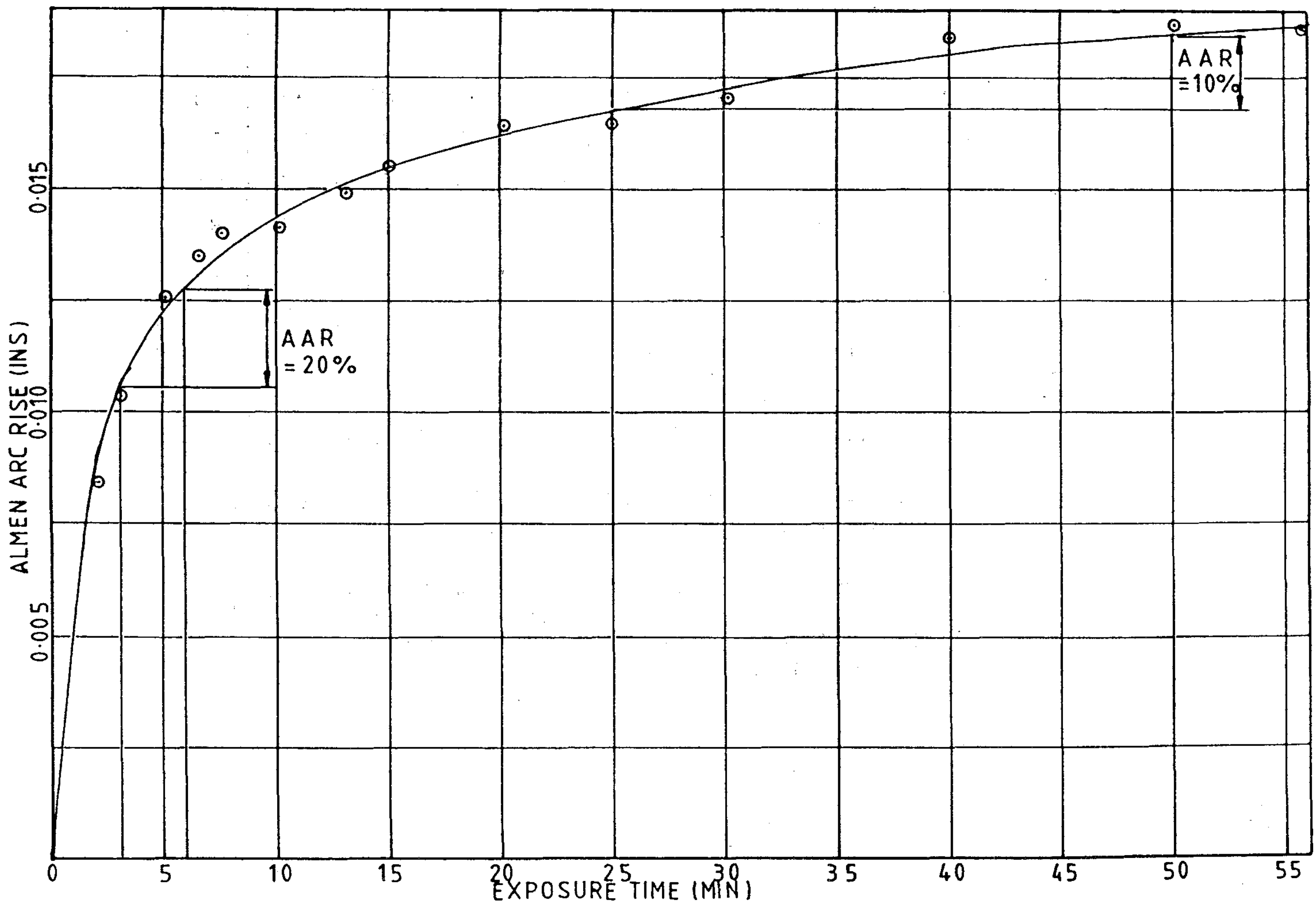


FIG 2 : ARC RISE CURVE FOR S.R.A.M.A. SHOT PEENING MACHINE

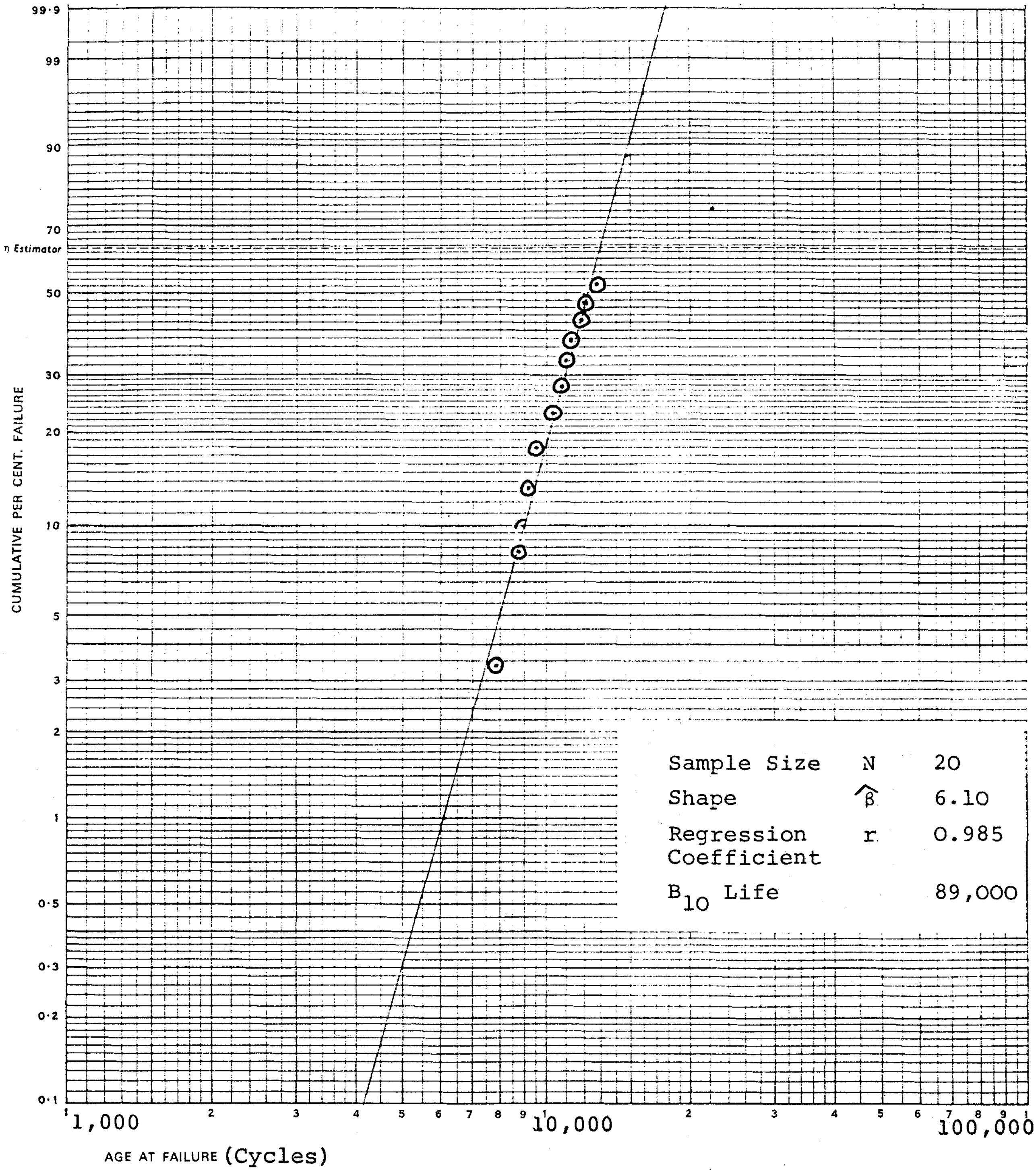


Fig 3: Weibull Plot of Fatigue Results for Carbon Steel
Material: Unpeened.

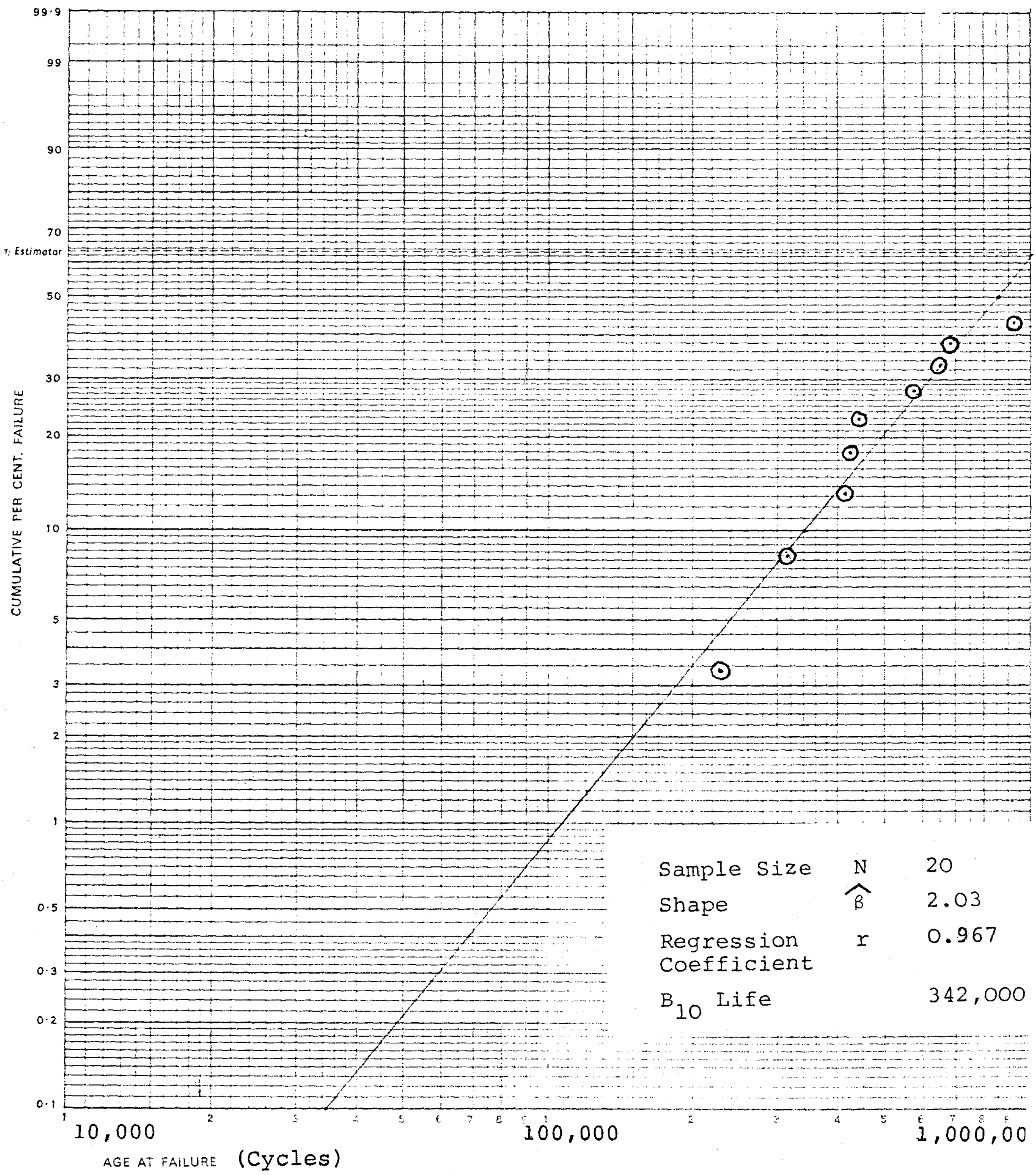


Fig 4: Weibull Plot of Fatigue Results for Carbon Steel Material: 3 Minutes Exposure.

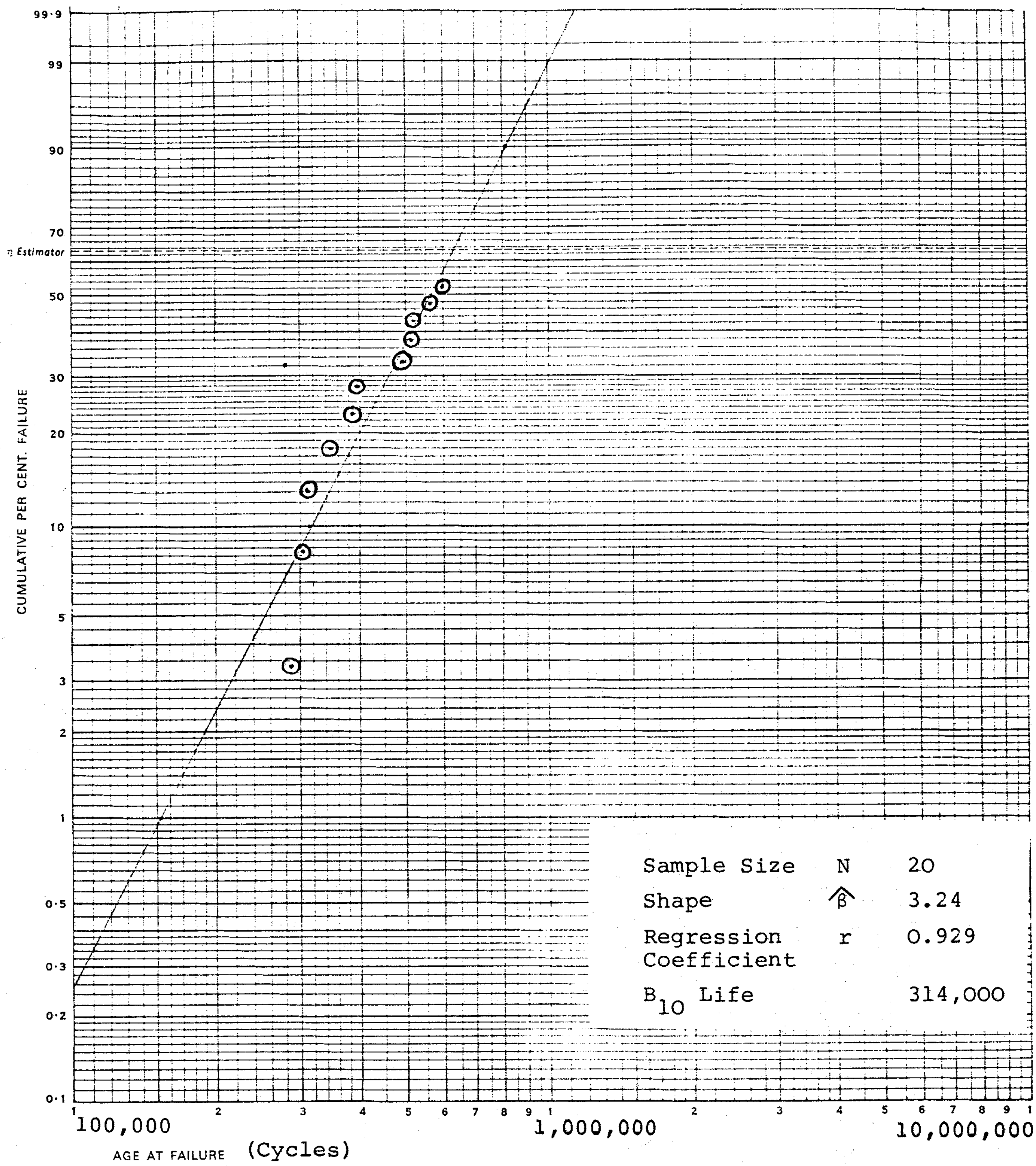


Fig 5: Weibull Plot of Fatigue Results for Carbon Steel Material: 6 Minutes Exposure.

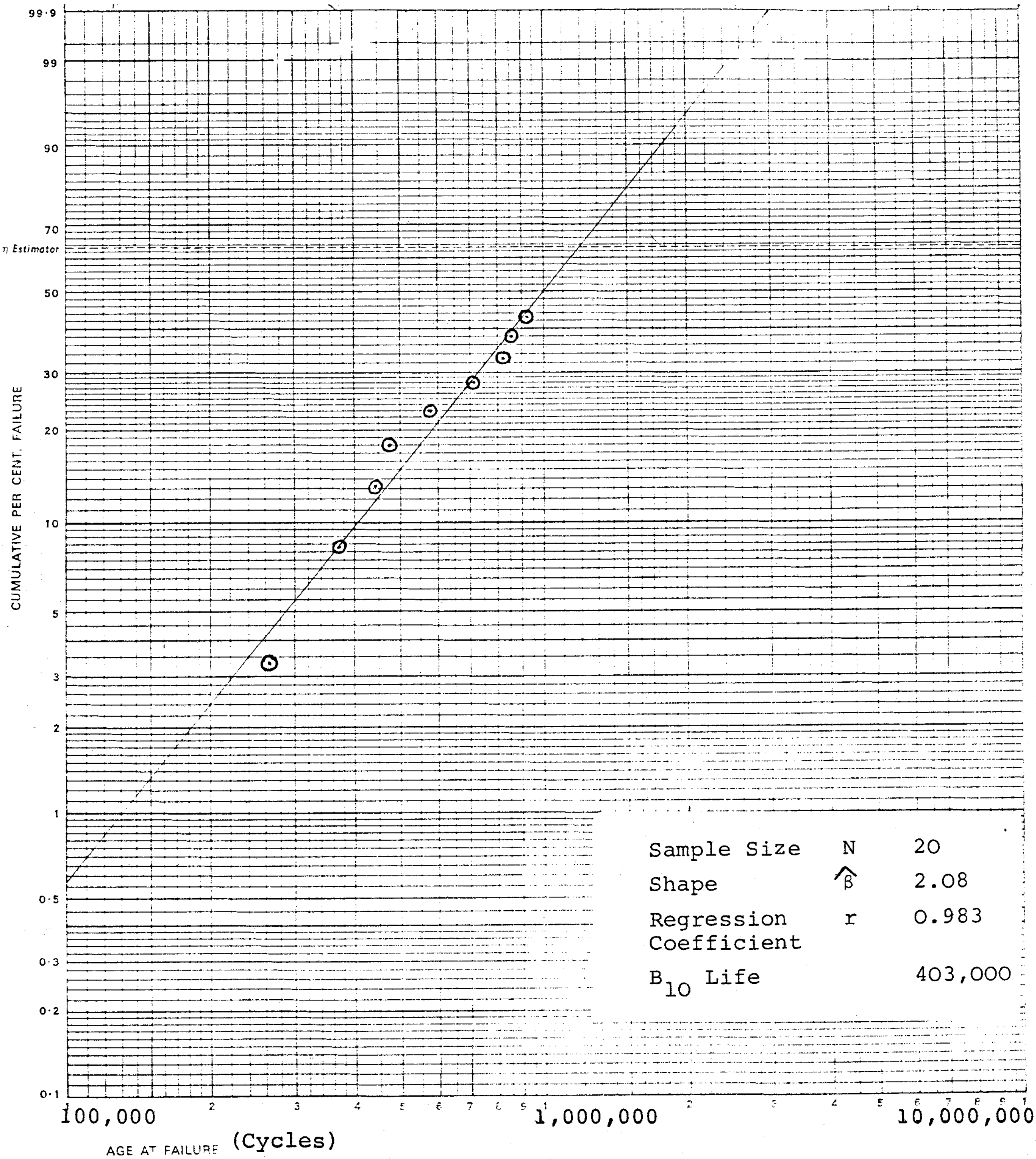


Fig 6: Weibull Plot of Fatigue Results for Carbon Steel Material: 10 Minutes Exposure.

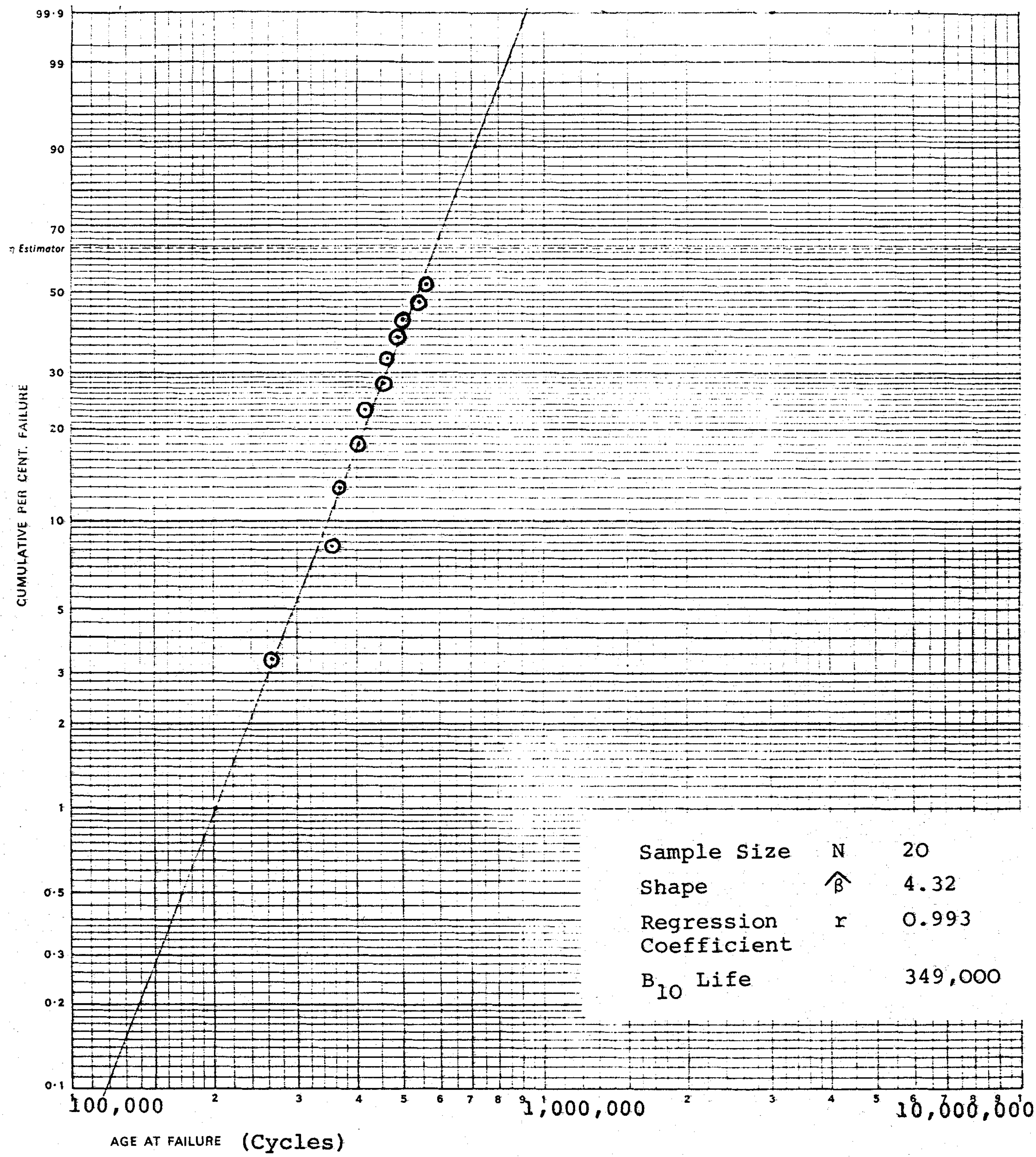


Fig 7: Weibull Plot of Fatigue Results for Carbon Steel Material: 16 Minutes Exposure.

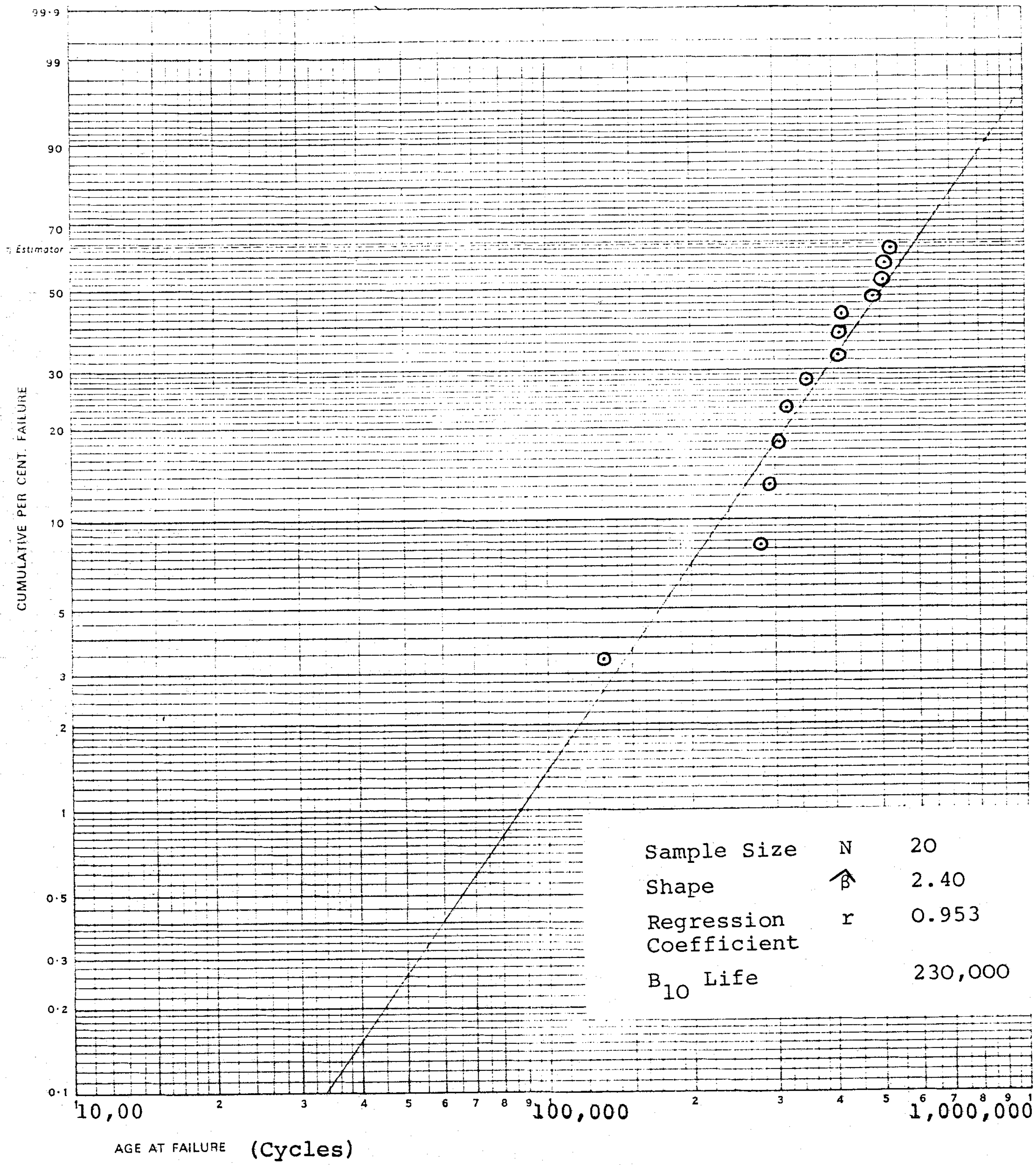


Fig 8: Weibull Plot of Fatigue Results for Carbon Steel Material: 25 Minutes Exposure.

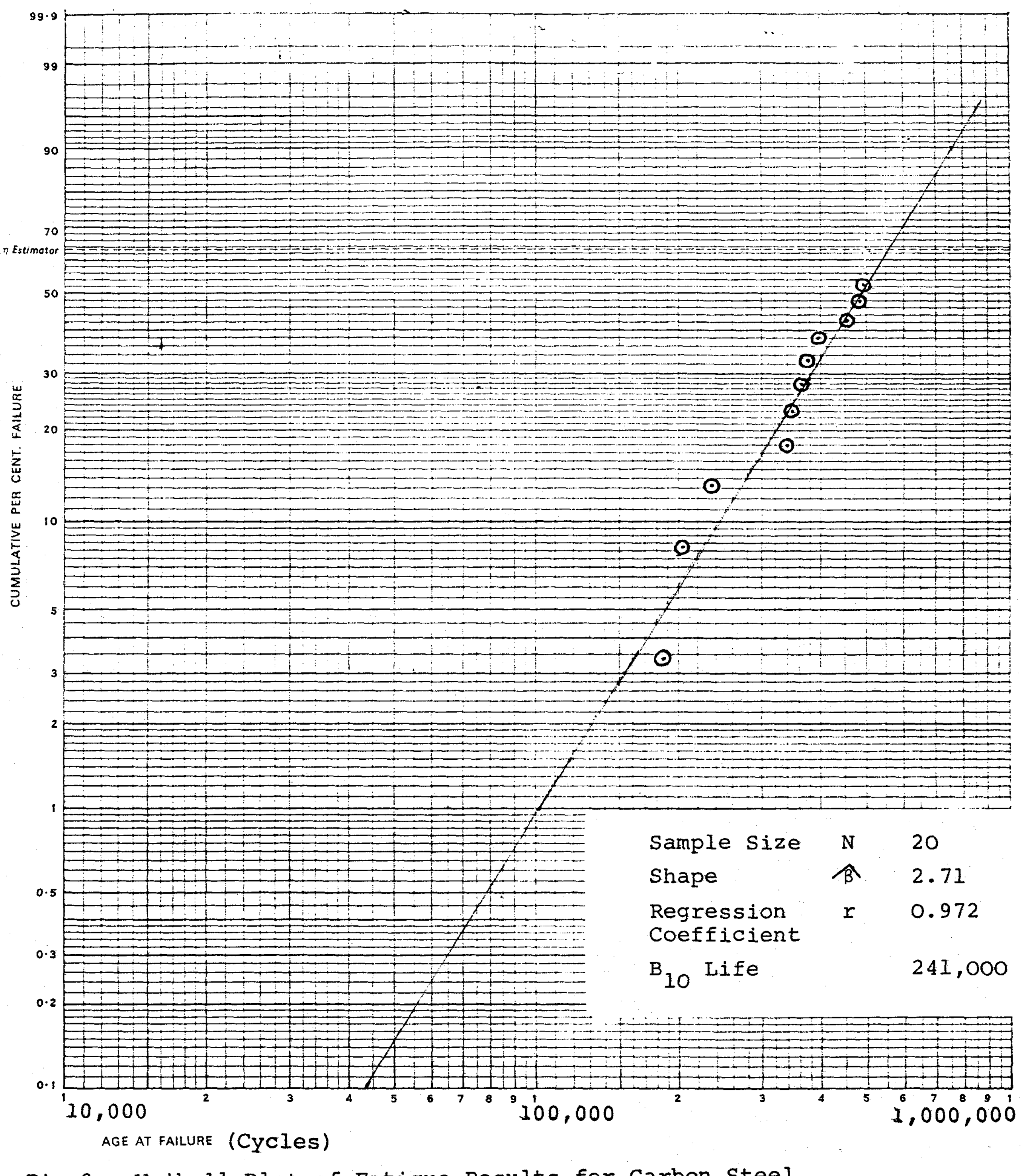


Fig 9: Weibull Plot of Fatigue Results for Carbon Steel Material: 35 Minutes Exposure.

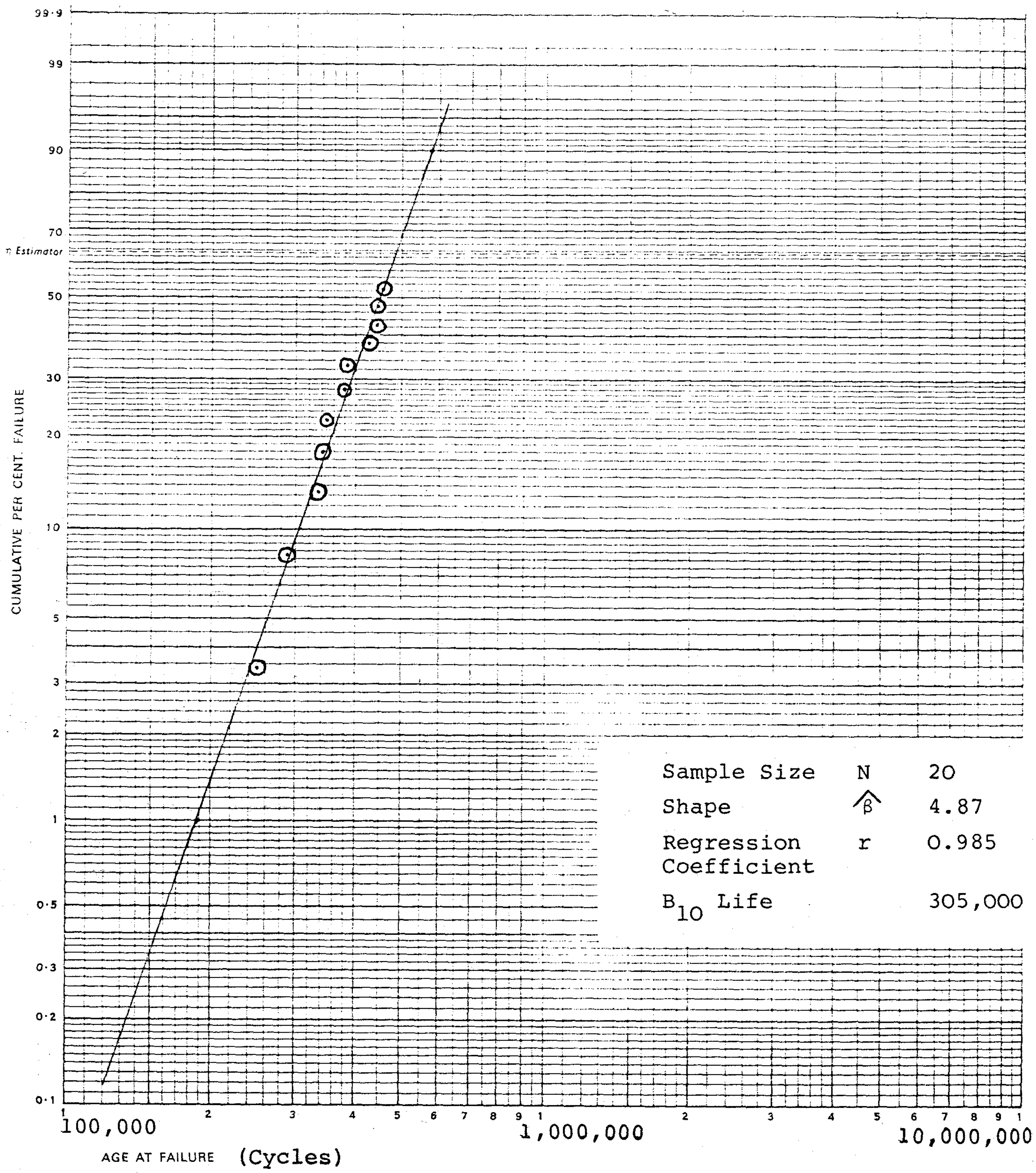


Fig 10: Weibull Plot of Fatigue Results for Carbon Steel Material: 50 Minutes Exposure.

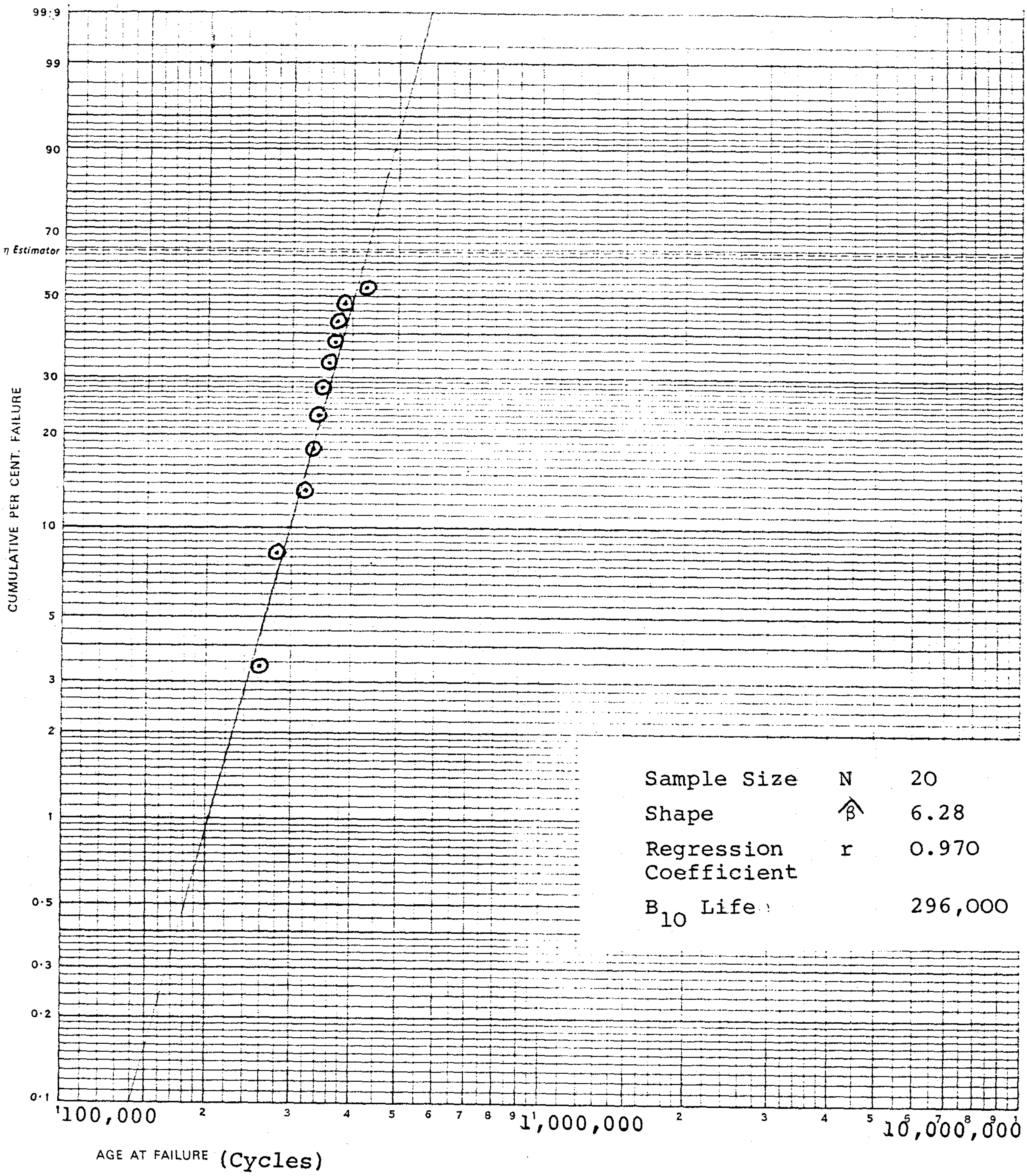


Fig 11: Weibull Plot of Fatigue Results for Carbon Steel Material: 75 Minutes Exposure.

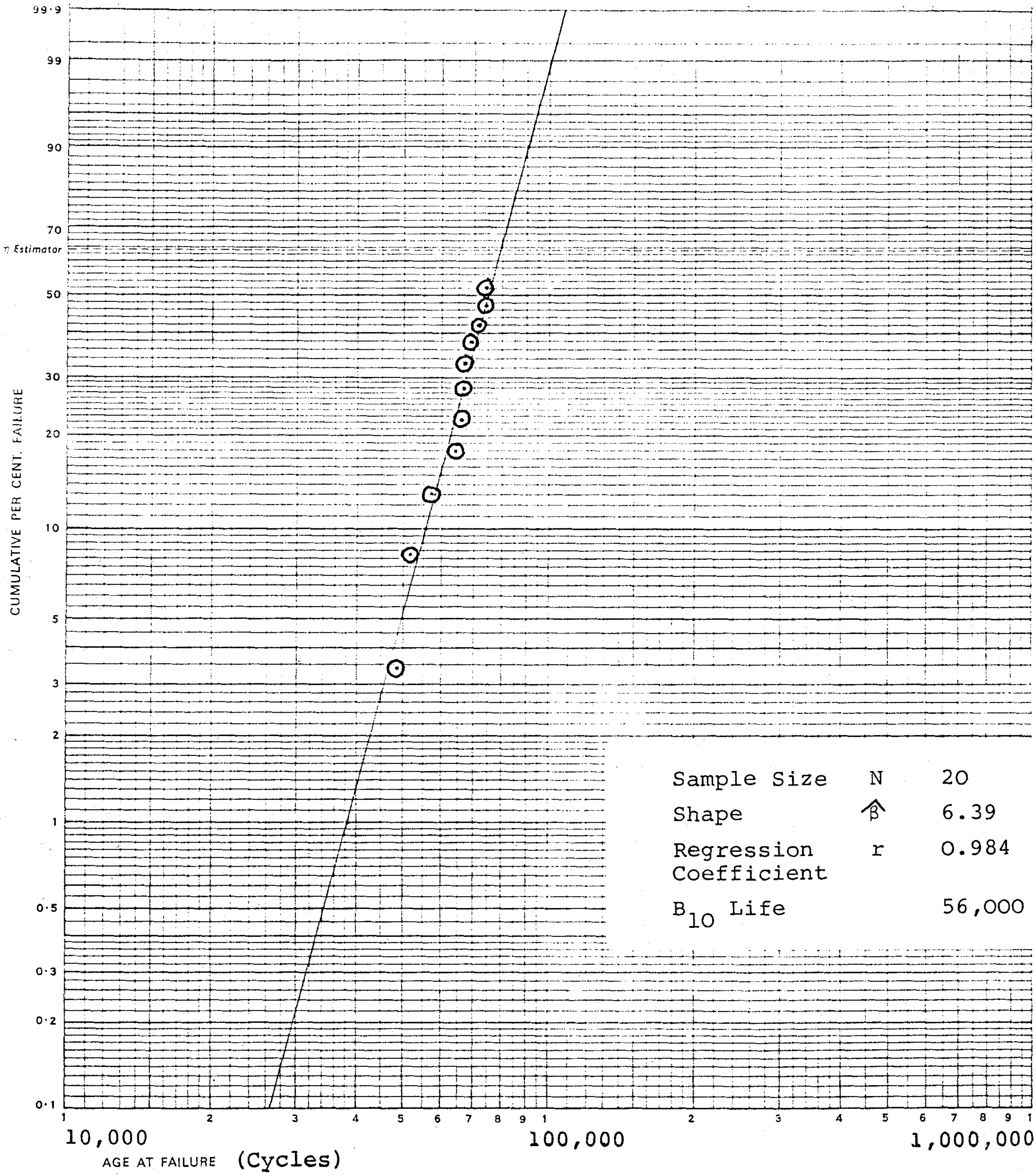


Fig 12: Weibull Plot of Fatigue Results for Chrome Vanadium Material: Unpeened.

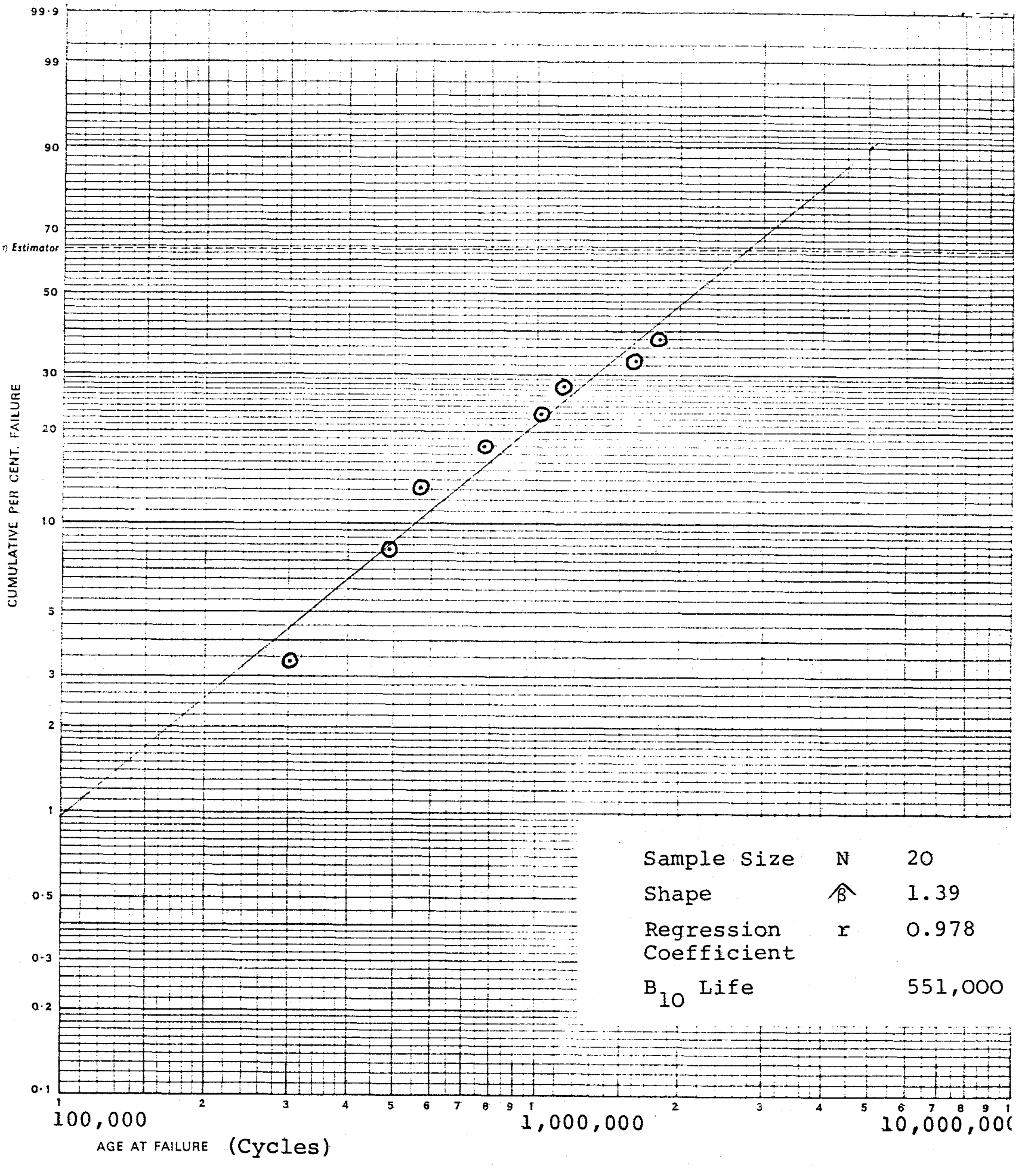


Fig 13: Weibull Plot of Fatigue Results for Chrome Vanadium Material: 3 Minutes Exposure.

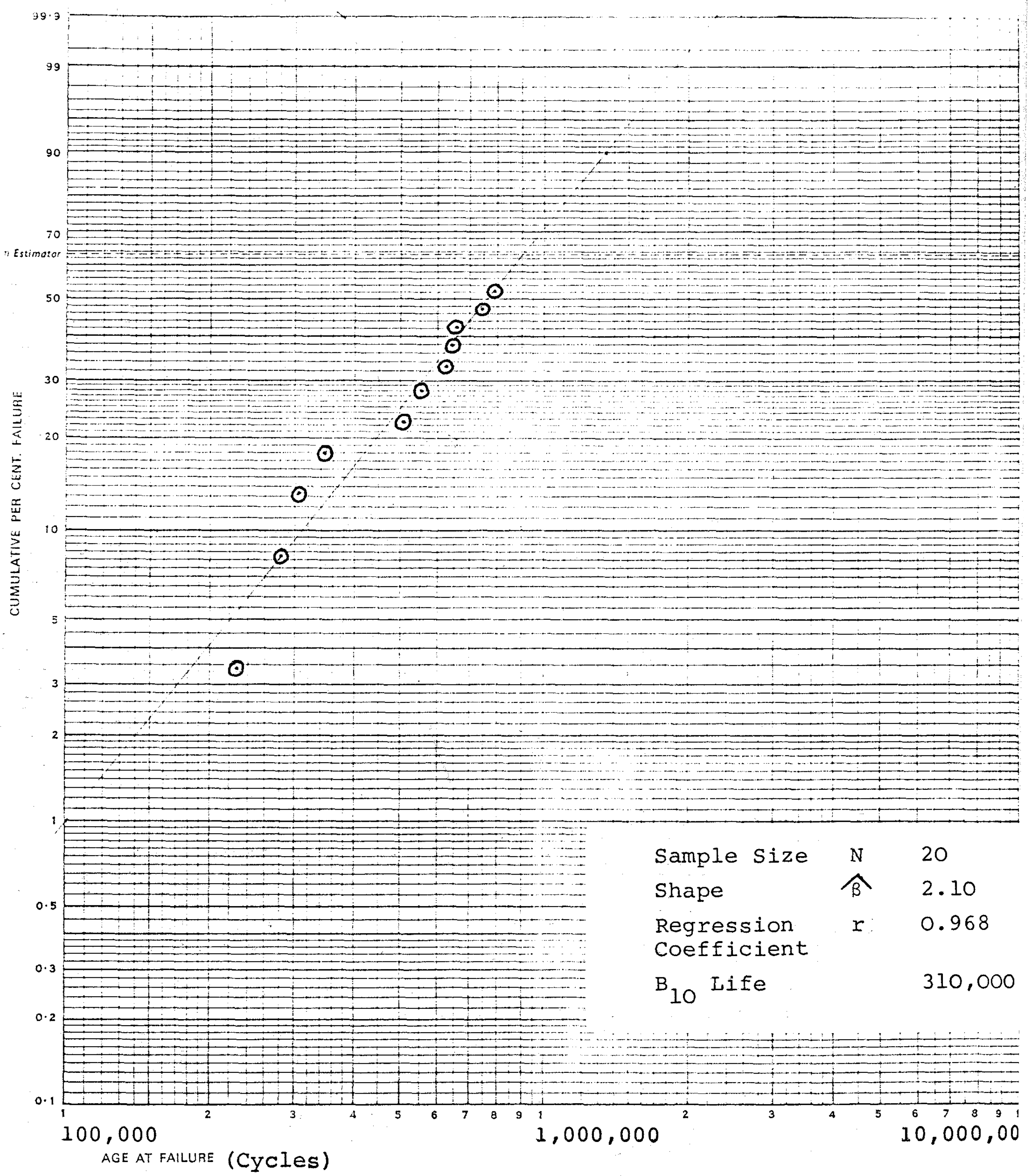


Fig 14: Weibull Plot of Fatigue Results for Chrome Vanadium Material: 6 Minutes Exposure.

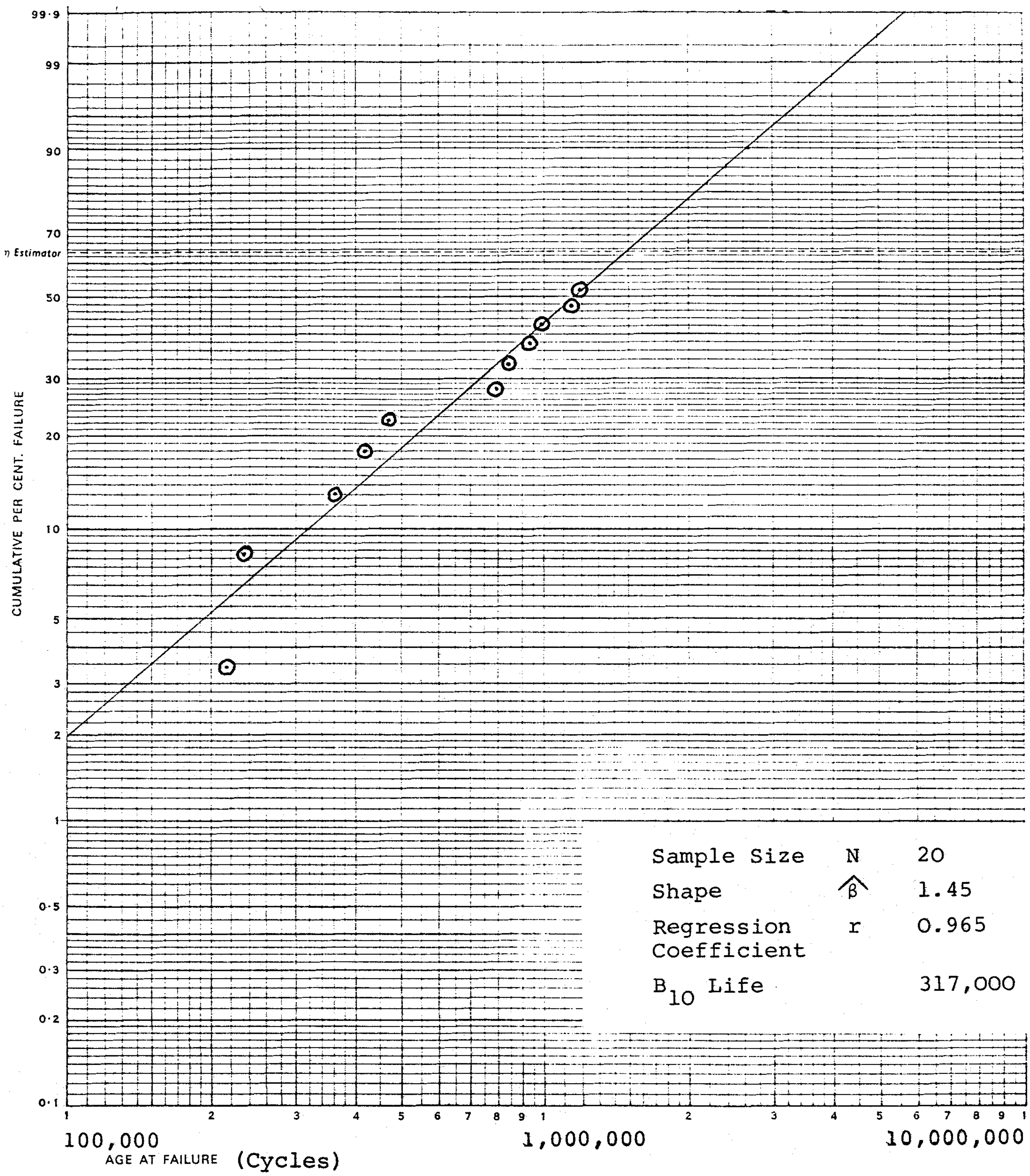


Fig 15: Weibull Plot of Fatigue Results for Chrome Vanadium Material: 10 Minutes Exposure.

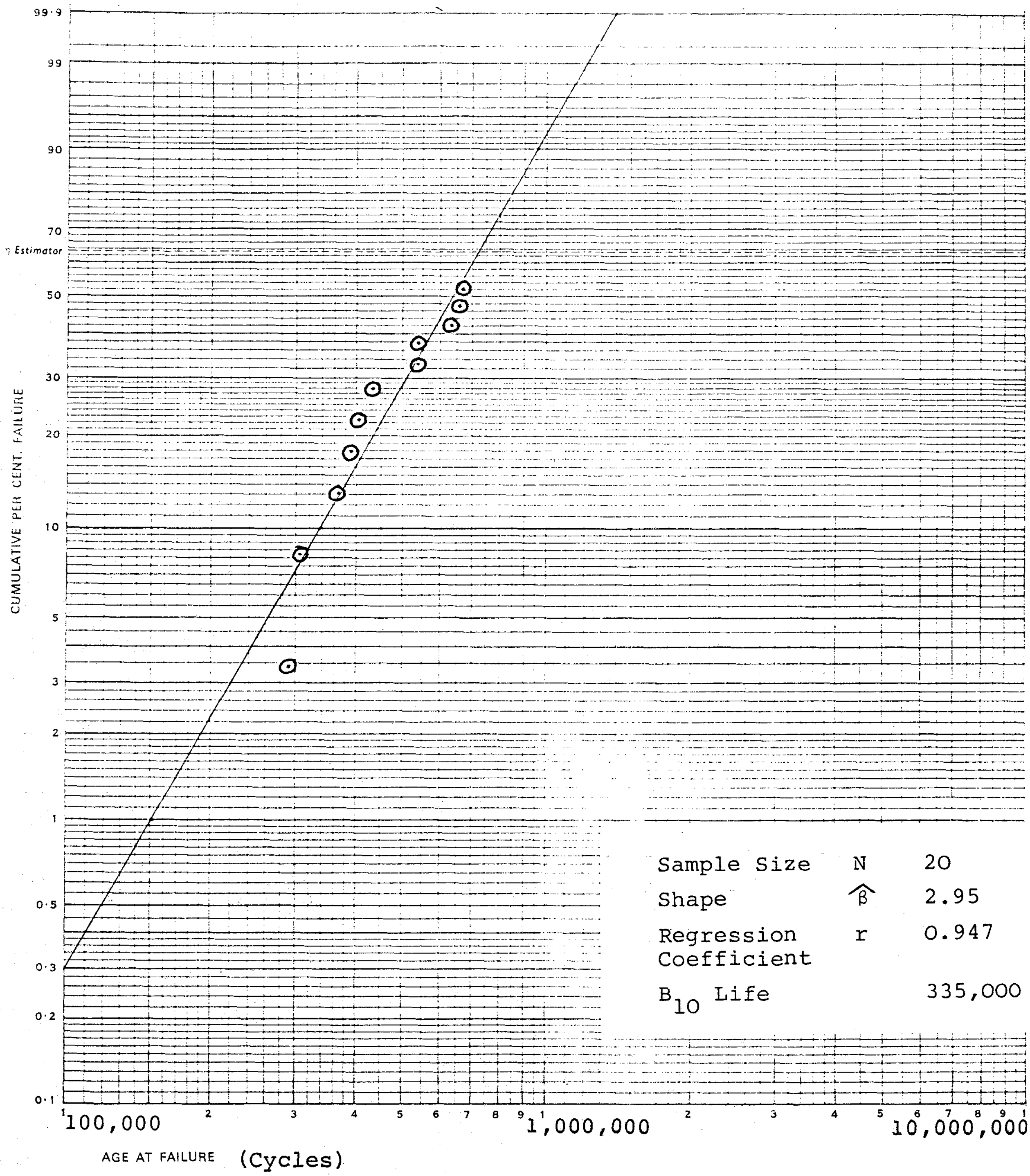


Fig 16: Weibull Plot of Fatigue Results for Chrome Vanadium Material: 16 Minutes Exposure Time

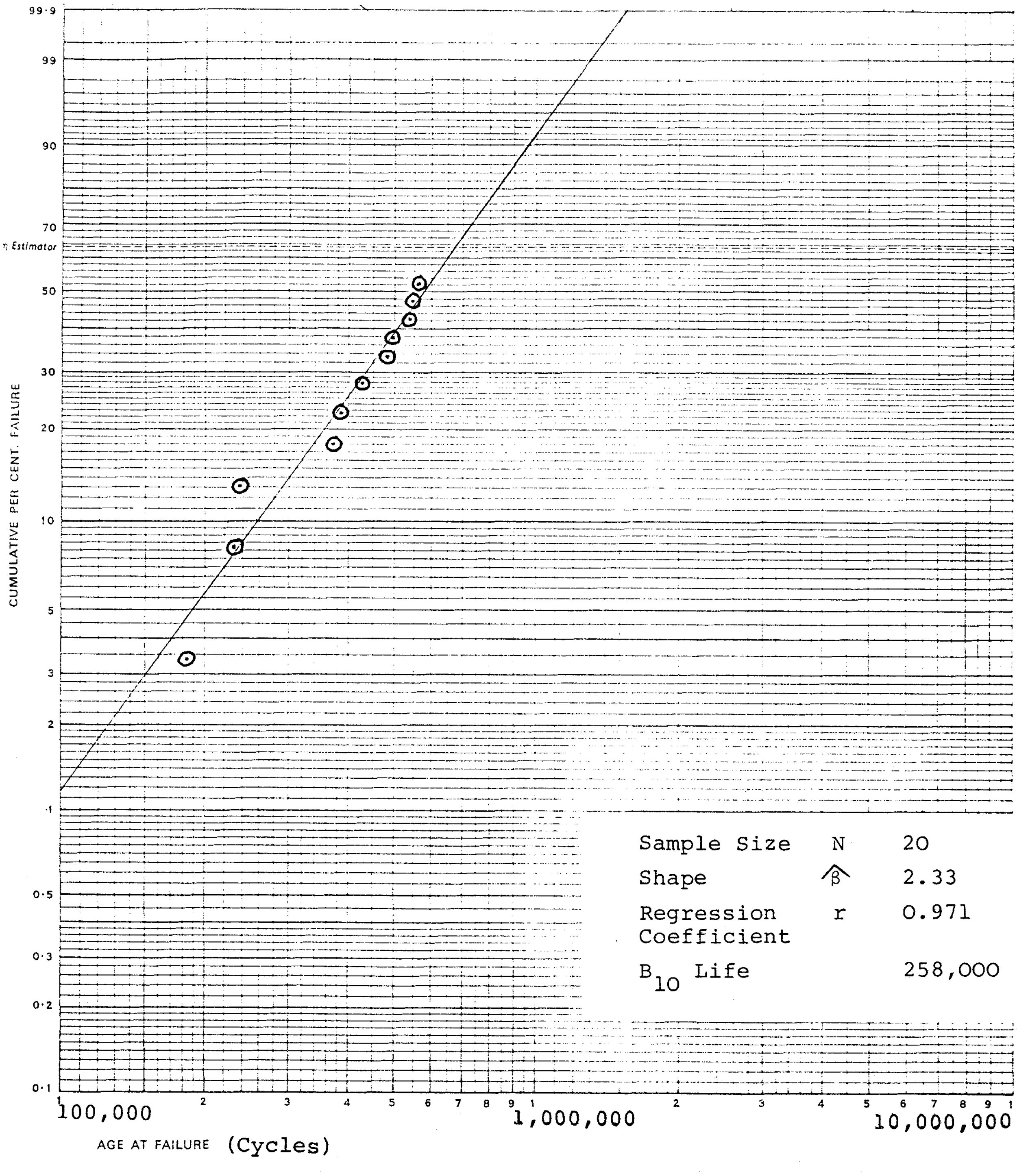


Fig 17: Weibull Plot of Fatigue Results for Chrome Vanadium Material: 25 Minutes Exposure.

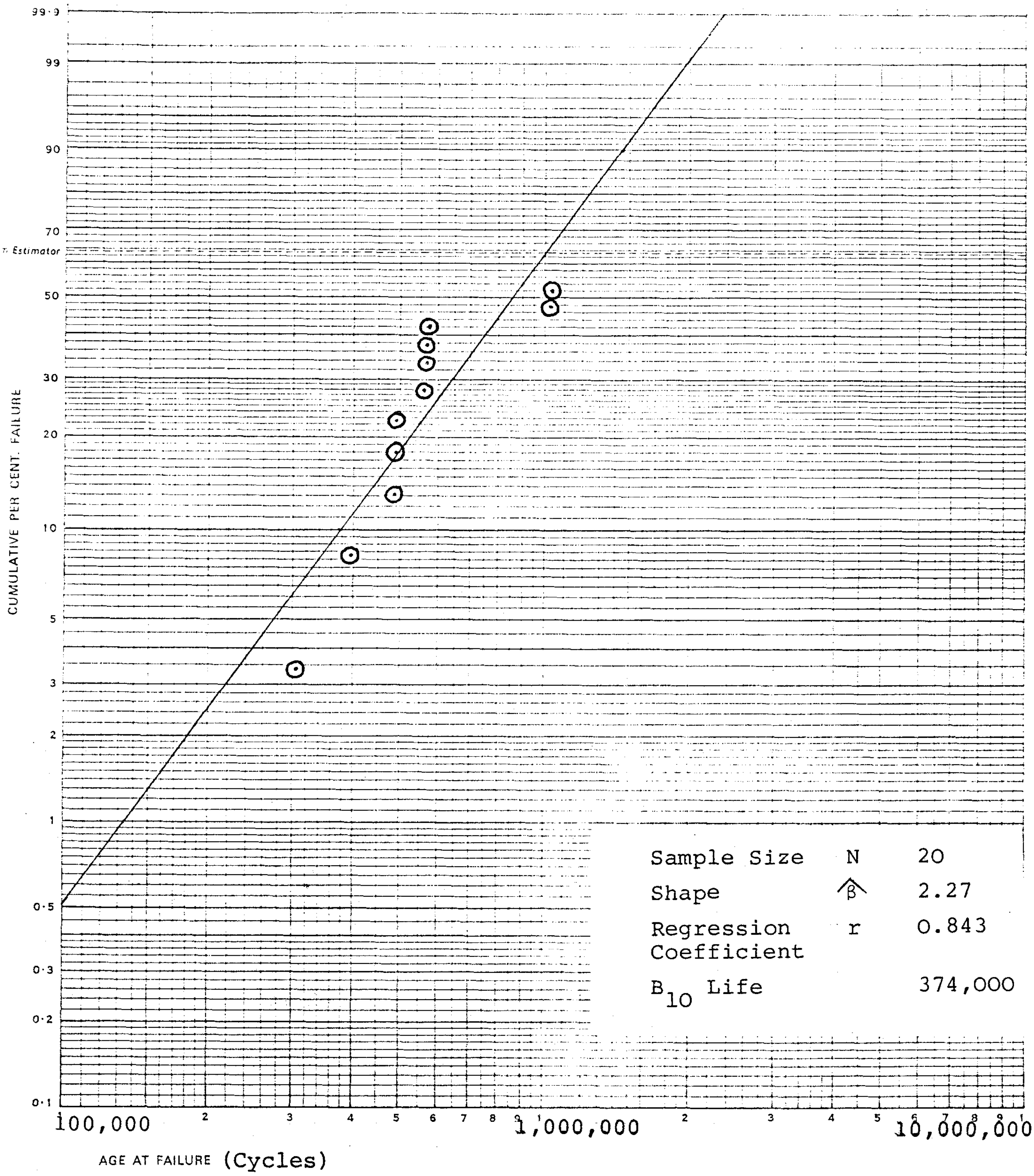


Fig 18: Weibull Plot of Fatigue Results for Chrome Vanadium Material: 35 Minutes Exposure.

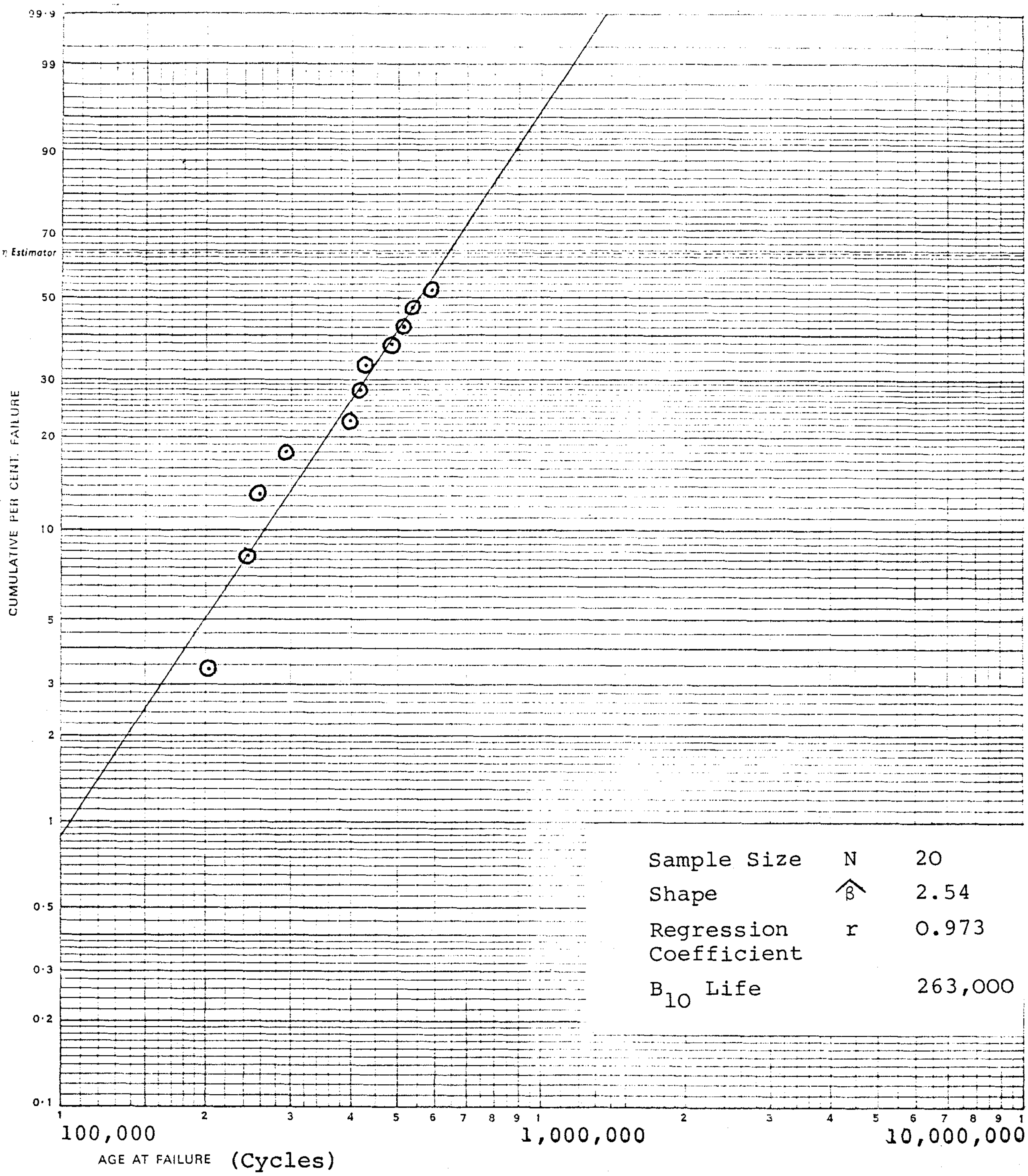


Fig 19: Weibull Plot of Fatigue Results for Chrome Vanadium Material: 50 Minutes Exposure.

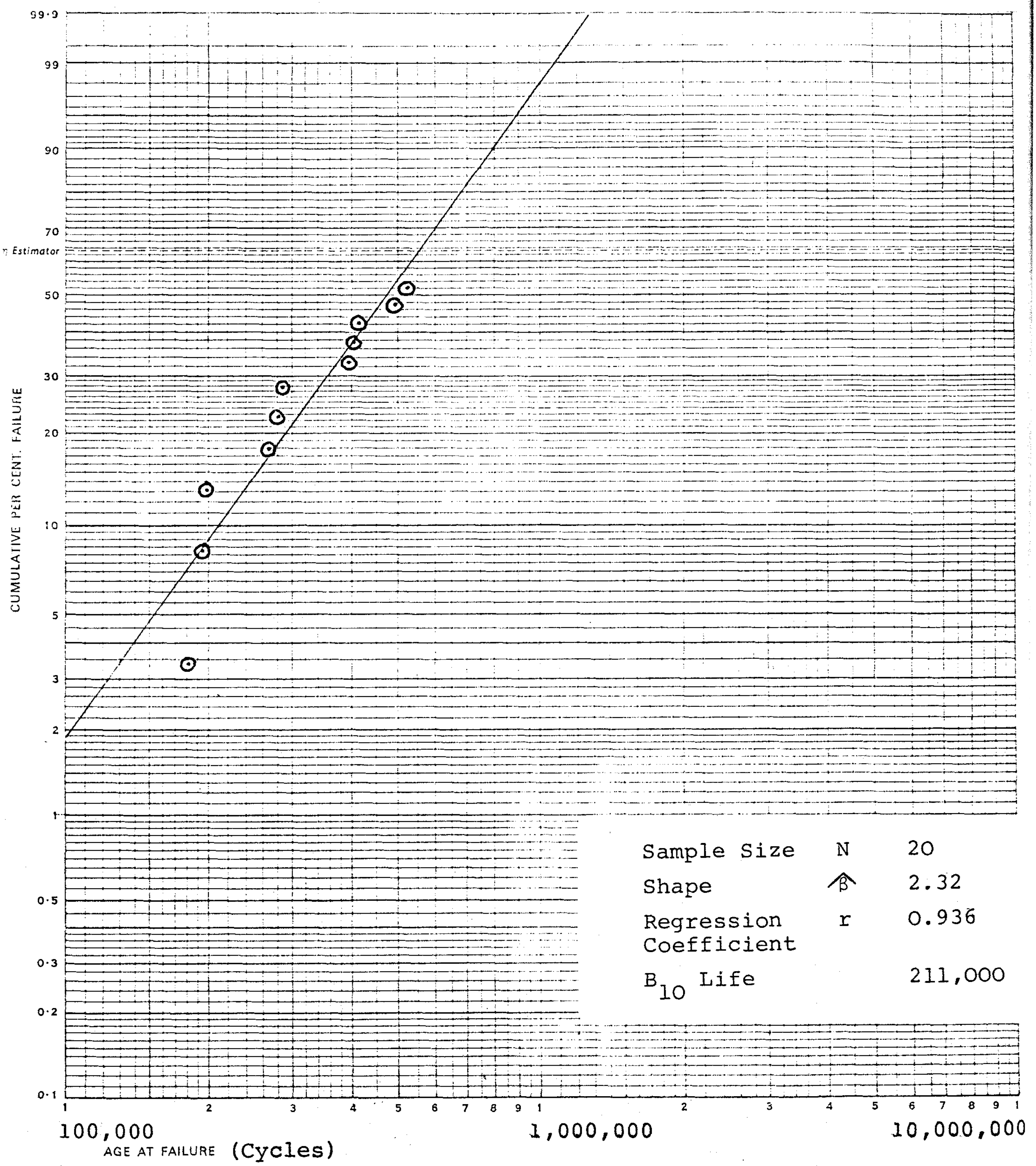


Fig 20: Weibull Plot of Fatigue Results for Chrome Vanadium Material: 75 Minutes Exposure.