THE SPRING RESEARCH ASSOCIATION

THE FATIGUE PROPERTIES OF HELICAL COMPRESSION SPRINGS MANUFACTURED FROM F.V. 520(S) WIRE

(Contract No. K43A/65/CB43A2)
Progress Report No. 5

by

S. D. Gray, A.P.(Sheff.), A.I.M.

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SUMMARY

Fatigue tests have been carried out on helical compression springs manufactured from F.V. 520(S) martensitic stainless steel wire, 4.0 mm (0.160 in) and 1.6 mm (0.064 in) diameter. Tests have also been carried out to determine the response to shot peening of springs made from 4.0 mm diameter wire.

Unpeened springs manufactured from 4.0 mm and 1.6 mm diameter wires showed similar fatigue performances at low initial stress levels to springs manufactured from 17-7 PH, S205, Armco 17-7 PH and B.S. 2056 wire.

Shot peening of F.V. 520(S) wire springs, made from 4.0 mm diameter wire, produced an elevation in fatigue strength at zero initial stress of well over 100%, a similar response to shot peening to that found with S205 springs.

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1. INTRODUCTION

The first commercial semi-austenitic precipitation hardening stainless steel was produced in the U.S.A. in the 1940's; since then a variety of steels, including the 17-7 PH type, has been produced. The only current British steel of this type is the F.V. 520(S), produced by Firth Vickers Stainless Steels Ltd. in 1956, and since that time F.V. 520(S) has been used in connection with aircraft and missile developments[1].

Until recently only bar, plate and strip have been available; however, in an attempt to extend the use of this material, cold drawn wire has been produced in the martensitic condition and in this particular programme is being assessed as a possible future spring material.

To complete the ambient temperature fatigue testing section of this current programme which was originally initiated by the SRA on behalf of the then Ministry of Defence (Aviation), fatigue data have been obtained on helical compression springs made from F.V. 520(S) wire. Two wire sizes have been examined, 4.0 mm and 1.6 mm (0.160 in and 0.064 in) diameter both having received a 75% reduction in area on drawing.

Additional tests have also been carried out to examine the response to shot peening of springs made from 4.0 mm diameter wire.

2. MATERIAL

2.1 Wire

Cold drawn F.V. 520(S) wire was obtained in the fully martensitic condition to two wire sizes, 4.0 mm (0.160 in) and 1.6 mm (0.064 in) diameter. Both wires had received the same 75% reduction in area on drawing, thereby allowing the effects of wire diameter on ageing and fatigue properties to be determined.

The wires were supplied in the unaged condition to tensile strengths of 1643 N/mm^2 (106.4 $tonf/in^2$) and 1504 N/mm^2 (97.4 $tonf/in^2$) for 4.0 mm and 1.6 mm diameter wires respectively. Close examination of the wire surfaces showed occasional relatively deep drawing marks. Such wire was discarded and not used in the investigation.

Both wires were produced from the same cast, and the actual chemical analysis is shown in Table I.

2.2 Springs

The design details of the springs tested in this programme are shown in Table II.

Coiling was carried out in the 'as-drawn' condition followed by a batch ageing treatment of 450°C for 2 hours.

Following end-grinding and cold prestressing, springs manufactured from 4.0 mm diameter wire were shot peened to an Almen Arc rise of 0.018/0.022 A2, and given a final low temperature heat treatment of 220°C for half an hour.

3. EXPERIMENTAL PROCEDURE

3.1 Mechanical Testing

Tensile and torsional data have been produced on both 4.0 mm and 1.6 mm wire, both in the "as-received" and aged conditions.

Tensile testing was carried out on a vertical Amsler testing machine equipped with an autographic stress-strain recorder.

Torsion testing was carried out on a Tinius Olsen 84.7 Nm (750 lbf/in) capacity multirange torsion testing machine, and a 5.6 Nm (50 lbf/in) Amsler torsion testing machine, the latter being used for the 1.6 mm diameter wire.

The results obtained are recorded in Tables III and IV.

3.2 Fatigue Testing

Load tests were carried out on individual springs to establish the necessary fatigue machine strokes to give the required stress ranges.

Springs were fatigue tested at two initial stress levels of 100 and 500 N/mm^2 (6.5 and 32.4 $tonf/in^2$) on forced-motion multiple spring testing machines. S/N curves have been produced, Figs. 1 to 6, and the necessary data extracted to construct modified Goodman diagrams, Figs. 7, 8 and 9.

The appropriate results from the broken springs were analysed statistically to provide 95 and 50% confidence lines, and to determine whether the correlation coefficient provided a significance of at least 95%.

4. DISCUSSION

4.1 Static Properties

Triplicate tensile and torsional tests were carried out on wire in the "as-received" and aged condition; the results obtained are presented in Tables III and IV.

4.1.1 4.0 mm Diameter Wire

From examination of the tensile data in Table III, it can be seen that this material had a good response to precipitation hardening. However, this response was not reflected in the torsional data due to severe wire delamination prior to failure (Fig. 10), as shown by the high number of twists to failure (Table IV).

4.1.2 1.6 mm Diameter Wire

In the "as received" condition the 1.6 mm diameter wire revealed a 10% lower U.T.S. even though both the 4.0 mm and 1.6 mm diameter wires were drawn from the same cast and to 75% reduction in area. This variation is attributed to a different wire drawing history. The response to ageing of both tensile and torsion properties was superior to that observed for 4.0 mm diameter wire. The aged wire possessed very little ductility as indicated by proof stress data, elongation and twist to failure results. No wire delamination was observed in 1.6 mm diameter wire.

4.2 Fatigue Properties

4.2.1 Unpeened Springs

From examination of Fig. 7 and Tables V and VI, it can be seen that at low initial stresses unpeened F.V. 520(S) springs manufactured from 4.0 mm diameter wire had very similar fatigue properties to springs manufactured from 4.0 mm diameter 17-7 PH and S205 wire, together with springs made from 2.6 mm diameter Armco 17-7 PH and B.S. 2056 wire. However, as the initial stress increased the F.V. 520(S) wire began to show slightly better properties than the S205 and 17-7 PH material.

Examination of the results in Fig. 8 for smaller diameter wires, showed unpeened springs made from 1.6 mm diameter F.V. 520(S) wire to be slightly inferior to springs manufactured from 17-7PH, S205 and Armco 17-7 PH wire, at all stress levels.

4.2.2 Shot Peened Springs

Fig. 7 shows the effect of shot peening on five spring materials, and it can be seen that the F.V. 520(S) had slightly better fatigue properties than the remaining qualities.

At zero initial stress the response to shot peening was similar to that for S205 springs with increases of over 100% being obtained, compared with 85% for 17-7 PH springs.

4.2.3 Effect of Wire Diameter

Comparison of the relative Goodman diagrams in Figs. 7 and 8 showed unpeened springs made from 4.0 mm diameter F.V. 520(S) wire to have almost identical fatigue properties, at all initial stress levels, to unpeened springs made from 1.6 mm diameter wire.

F.V. 520(S) springs which had not broken after completing 10^7 cycles were load tested to establish the amount of relaxation and to check that delamination had not occurred during testing. The results showed that none of the springs had relaxed, however a few had recovered by approximately 2%.

4.2.4 Limited Life Fatigue Data

Table V and Fig. 9 compare the limited life and fatigue limit data for springs manufactured from 4.0 mm and 1.6 mm diameter wires. As described earlier in this report the 10^7 cycles fatigue data for unpeened springs made from 4.0 mm and 1.6 mm diameter wire are very similar, however the limited life data suggest that the 1.6 mm diameter wire possesses superior fatigue properties to 4.0 mm diameter wire, at lower endurances. The 10^6 cycles data for 4.0 mm diameter wire show the material to respond to shot peening to a greater extent than that indicated by the fatigue limit data.

4.2.5 Fatigue Ratios

Table VI compares the fatigue ratios, i.e. fatigue strength at zero initial stress divided by the ultimate tensile strength, for F.V. 520(S), S205 and 17-7 PH wire. It can be seen that all these materials possess similar fatigue ratios.

4.3 Examination of Spring Failures

4.3.1 Unpeened Springs

A 45^{o} type helicoidal fracture face was observed on all springs tested at high initial stress levels, with failures occurring approximately half-way along each spring. Examination of the fracture zone showed crack initiation to occur at the inside radius of the spring, with a continuous crack running along the inside radius to the end of the spring.

At low stress levels a more longitudinal fracture zone was observed, again with wire showing a "shred" type fracture and continuous cracks, along the inside spring radius.

4.3.2 Shot Peened Springs

Springs in the shot peened condition showed very similar fracture characteristics to those observed for unpeened springs.

In general, fractures occurred approximately $1\frac{1}{2}$ coils from one end, the whole spring showing longitudinal cracks along the inside radius, as observed for unpeened springs.

The spring failures observed with F.V. 520(S) wire, apart from delamination, were similar to those seen for 17-7 PH wire and described in an earlier report[2].

5. CONCLUSIONS

1. Unpeened springs made from 4.0 mm and 1.6 mm diameter F.V. 520(S) wire, revealed very similar fatigue performances.

2. Both the 1.6 mm and 4.0 mm diameter wire received approximately the same amount of reduction on drawing (75%) but exhibited different tensile strengths. In addition different responses to ageing were noted.

3. Springs made from 1.6 mm diameter F.V. 520(S) wire revealed a slightly inferior fatigue performance to unpeened springs manufactured from 17-7 PH, S205 and Armco 17-7 PH wire at all stress levels.

4. Unpeened and shot peened springs manufactured from 4.0 mm diameter F.V. 520(S) wire showed very similar fatigue properties to springs made from 17-7 PH, S205, Armco 17-7 PH and B.S. 2056 wire.

5. F.V. 520(S) springs revealed a similar response to shot peened S205 springs, showing increases in fatigue strength of over 100% at zero initial stress.

6. REFERENCES

1. Morley J. I. "Further Development in F.V. 520 Steel", Firth Vickers Publication No. 528, p.7.

2. Gray S. D. "The Fatigue Properties of Helical Compression Springs Manufactured from 17-7 PH wire", SRA Report No. 198.

TABLE I

CHEMICAL COMPOSITION OF F.V. 520(S) WIRE

%C	%Si	%Mn	%Cr	%Ni	%Cu	%Mo	%Ti	%S	%P
0.048	0.37	1.05	16.18	5.47	2.08	1.72	0.10	0.014	0.020

TABLE II

SPRING DESIGN DATA

	4.0 mm		1.6 mm	
	METRIC	IMPERIAL	METRIC	IMPERIAL
Spring Mean Diameter	26.9 mm	1.05 in	11.0 mm	0.4 in
No. of Active Coils	3.5	3.5	3.5	3.5
Total No. of Coils	5.5	5.5	5.5	5.5
Spring Index	6.5	6.5	6.9	6.9
Free Length After Grinding and Prestressing	50.0 mm	2.0 in	22.0 mm	0.9 in
Prestressed Solid Stress	1282 N/mm^2	83.0 $tonf/in^2$	1459 N/mm^2	94.4 $tonf/in^2$

TABLE III

TENSILE DATA FOR F.V. 520(S) QUALITY WIRE

WIRE DIAMETER	CONDITION	ULTIMATE TENSILE STRENGTH		PROOF STRESS						REDUCTION IN AREA %	ELONGATION % (2 in G.L.)
				0.1%		0.2%		0.5%			
		N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2		
4.0 mm	As	1628	105.4	1137	73.6	1344	87.0	1574	101.9	46.0	4
(0.160 in)	Drawn	1651	106.9	1259	81.5	1419	91.9	1566	101.4	50.0	4
		1651	106.9	1282	83.0	1444	93.5	1597	103.4	46.0	4
MEAN VALUES		1643	106.4	1225	79.3	1402	90.8	1578	102.2	47.5	4
4.0 mm	Aged	1843	119.3	1719	111.3	1813	117.4	-	-	46.0	2
(0.160 in)	450°C	1888	122.3	1813	117.4	1843	119.3	-	-	46.0	2
	-2hrs	1805	116.9	1699	110.0	1760	114.0	-	-	48.0	2
MEAN VALUES		1846	119.5	1744	112.9	1805	116.9	-	-	46.6	2
1.6 mm	As	1488	96.4	1200	77.7	1440	93.2	-	-	28.1	5
(0.064 in)	Drawn	1488	96.4	1248	80.8	1368	88.6	-	-	28.1	5
		1536	99.5	1272	82.4	1344	87.0	-	-	28.1	5
MEAN VALUES		1504	97.4	1240	80.3	1384	89.6	-	-	28.1	5
1.6 mm	Aged	1775	114.9	-	-	-	-	-	-	32.0	1
(0.064 in)	450°C	1751	113.4	-	-	-	-	-	-	30.0	1
	-2hrs	1730	112.0	-	-	-	-	-	-	32.0	2
MEAN VALUES		1751	113.4	-	-	-	-	-	-	31.3	1.3

TABLE IV

TORSIONAL DATA FOR F.V. 520(S) QUALITY WIRE

WIRE DIAMETER	CON-DITION	MAXIMUM SHEAR STRESS		PROOF STRESS						TWISTS TO FAILURE
				0.1%		0.2%		0.5%		
		N/mm^2	$tonf/in^2$	N/mm^2	$tonf/in^2$	N/mm^2	$tonf/in^2$	N/mm^2	$tonf/in^2$	
4.0 mm (0.160 in)	As Drawn	1328	86.0	830	53.7	927	60.0	-	-	8
		1303	84.4	758	49.1	848	54.9	-	-	7
		1287	83.3	746	48.3	905	58.6	-	-	7
MEAN VALUES		1307	84.6	778	50.4	893	57.8	-	-	7
4.0 mm (0.160 in)	Aged 450°C 2 hrs	1353	87.6	1155	74.8	-	-	-	-	15
		1371	88.8	1120	72.5	-	-	-	-	18
		1387	89.8	1155	74.8	-	-	-	-	20
MEAN VALUES		1369	88.7	1142	74.0	-	-	-	-	17
1.6 mm (0.064 in)	As Drawn	1035	67.0	642	41.6	683	44.2	884	57.2	25
		1045	67.6	589	38.2	697	45.1	871	56.4	26
		1045	67.6	709	45.9	791	51.2	911	60.0	25
MEAN VALUES		1042	67.4	647	42.0	724	46.8	887	57.9	25
1.6 mm (0.064 in)	Aged 450°C 2 hrs	1205	78.0	1072	69.4	1138	73.7	1178	76.3	2
		1239	80.2	1138	73.7	1178	76.3	1232	79.8	2
		1219	78.9	1124	72.8	1178	76.3	1205	78.0	2
MEAN VALUES		1221	79.0	1111	72.0	1165	75.4	1205	78.0	2

TABLE V FATIGUE DATA FOR F.V. 520(S) SPRINGS

WIRE DIAMETER (mm)	SURFACE CONDITION	INITIAL STRESS		FATIGUE STRENGTH					
				10^5		10^6		10^7	
		N/mm^2	$tonf/in^2$	N/mm^2	$tonf/in^2$	N/mm^2	$tonf/in^2$	N/mm^2	$tonf/in^2$
4.0	Unpeened	100	6.5	890	57.6	640	41.4	500	32.4
4.0	Unpeened	500	32.4	-	-	1010	65.4	900	58.3
4.0	Shot Peened	100	6.5	-	-	1080	69.9	900	58.3
4.0	Shot Peened	500	32.4	-	-	1220	78.9	1100	71.2
1.6	Unpeened	100	6.5	1020	66.0	780	50.5	560	36.3
1.6	Unpeened	500	32.4	-	-	1080	69.9	940	60.9

TABLE VI THE FATIGUE RATIOS OF SOME SPRING MATERIALS

SRA REPORT NO.	MATERIAL	WIRE DIAMETER	SURFACE CONDITION	FATIGUE RATIOS $\frac{f}{u}$ AT ZERO INITIAL STRESS
208	F.V. 520(S)	4.0 mm 4.0 mm 1.6 mm	U/P S/P U/P	0.22 0.46 0.27
198	17-7 PH	4.0 mm 4.0 mm 1.6 mm	U/P S/P U/P	0.27 0.50 0.30
206	S205	4.0 mm 4.0 mm 1.6 mm	U/P S/P U/P	0.24 0.52 0.32

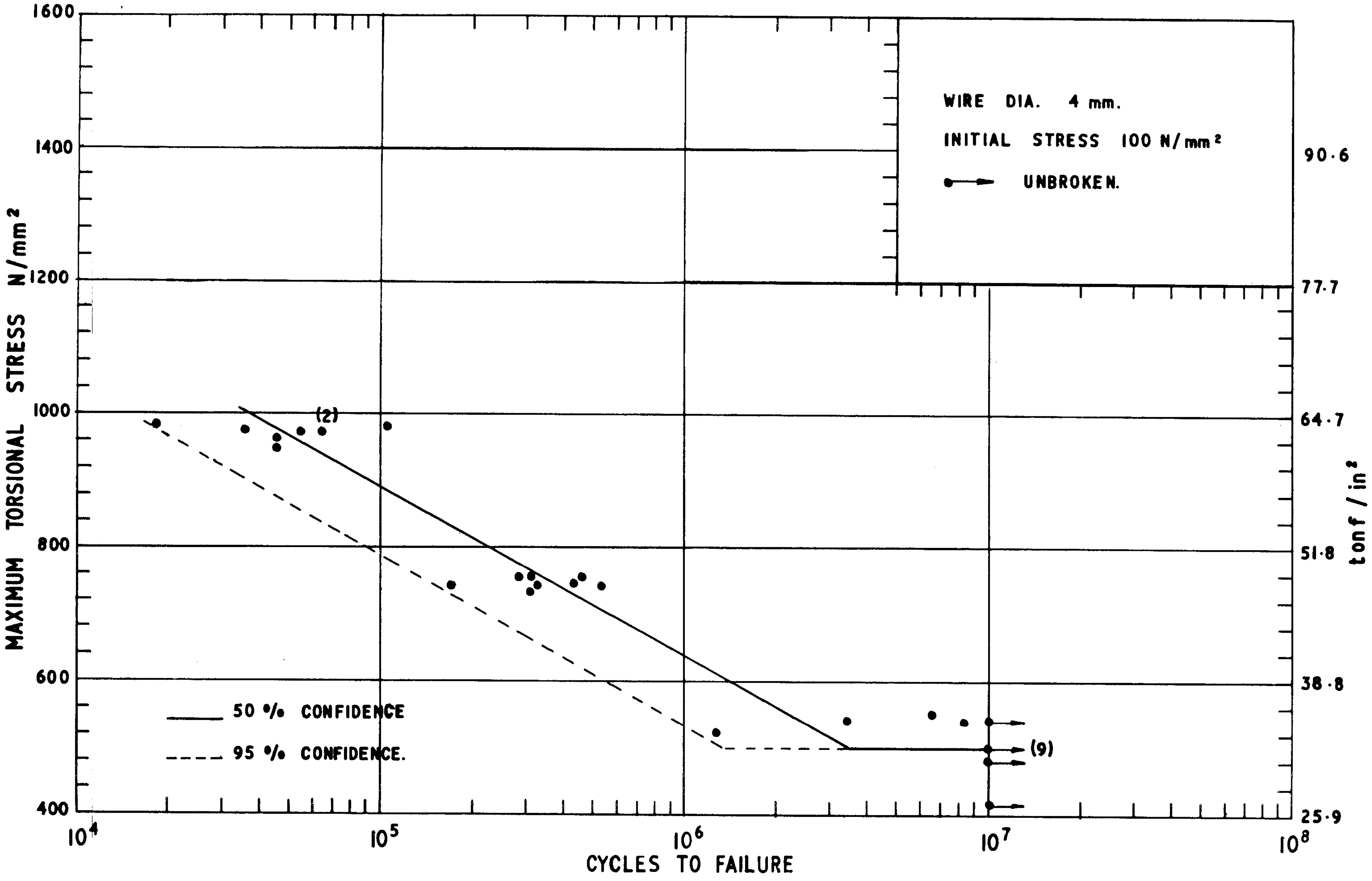

FIG. I S/N CURVE FOR F.V. 520 (S) UNPEENED SPRINGS.

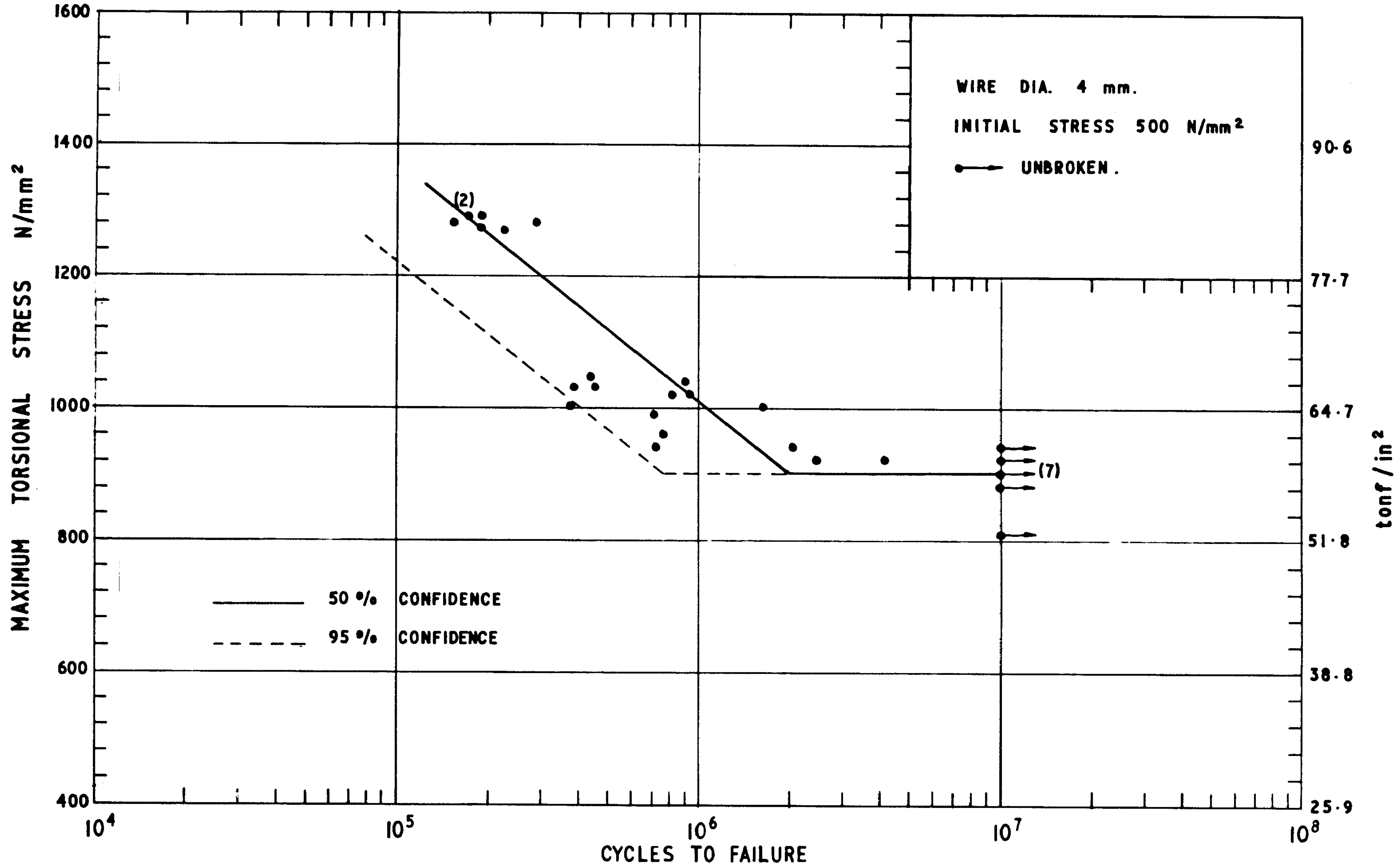

FIG. 2. S/N CURVE FOR F.V. 520 (S) UNPEENED SPRINGS.

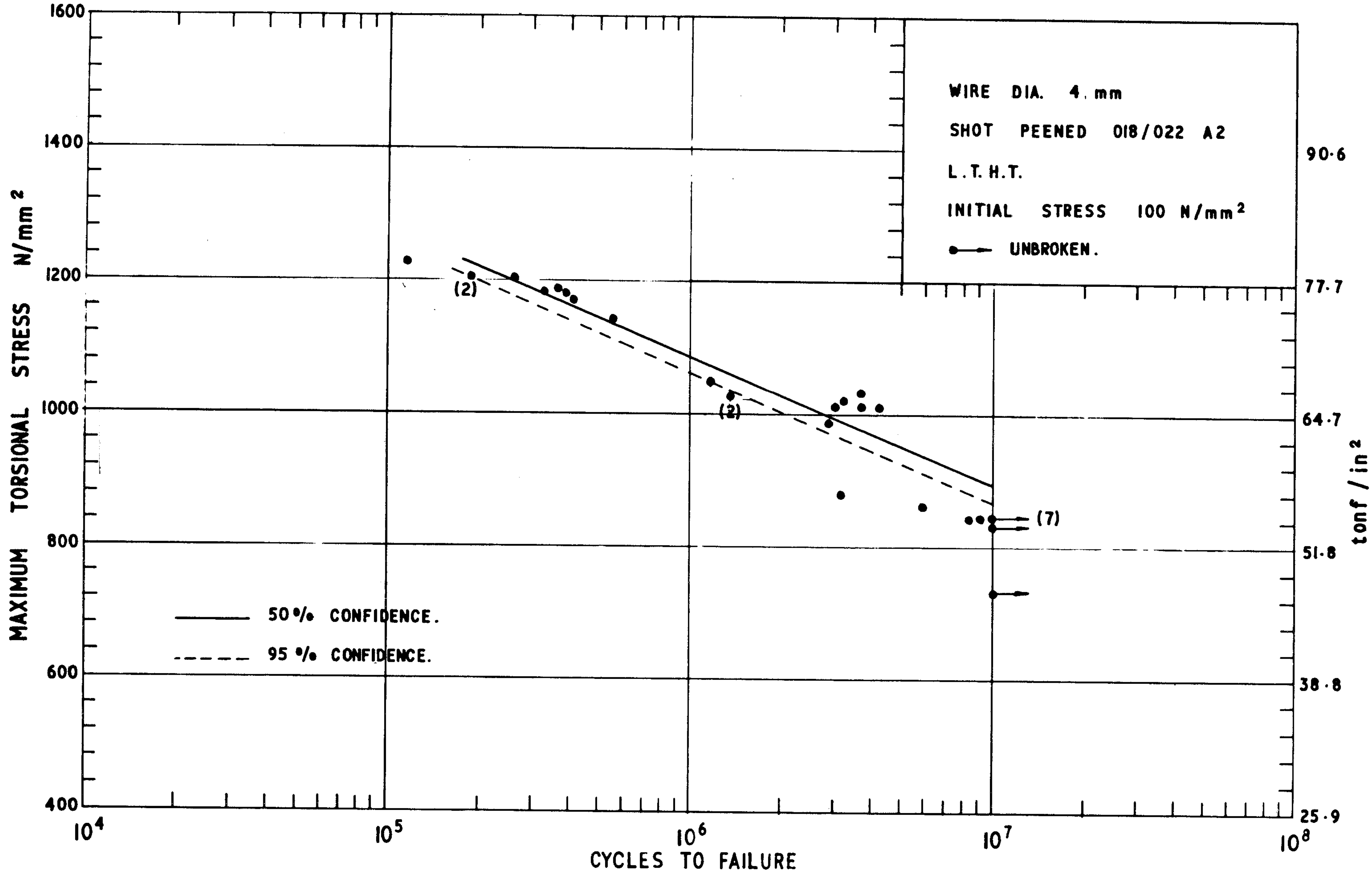

FIG. 3. S/N CURVE FOR F.V. 520 (S) SHOT PEENED SPRINGS.

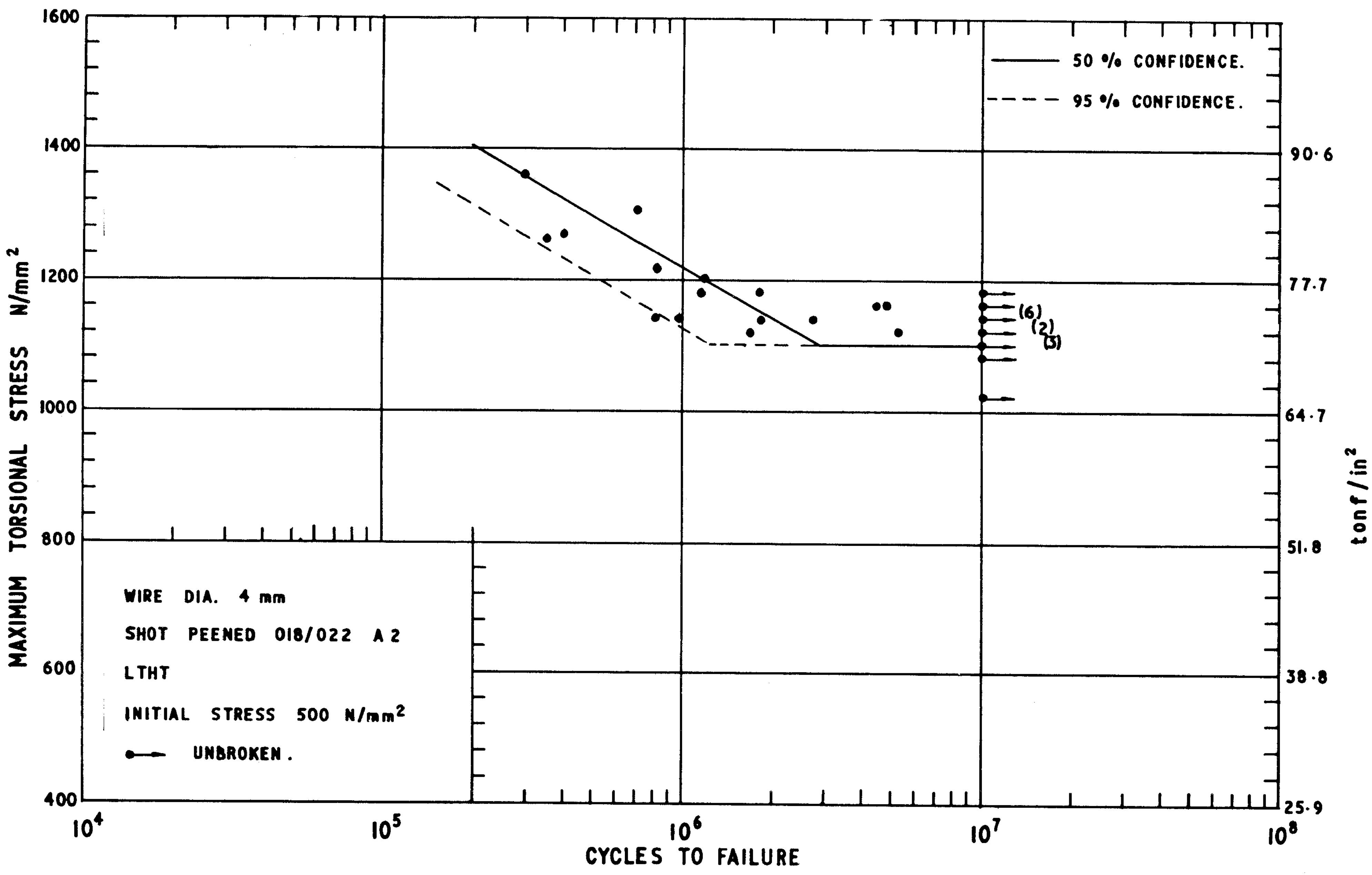

FIG. 4 S/N CURVE FOR F.V. 520 (S) SHOT PEENED SPRINGS.

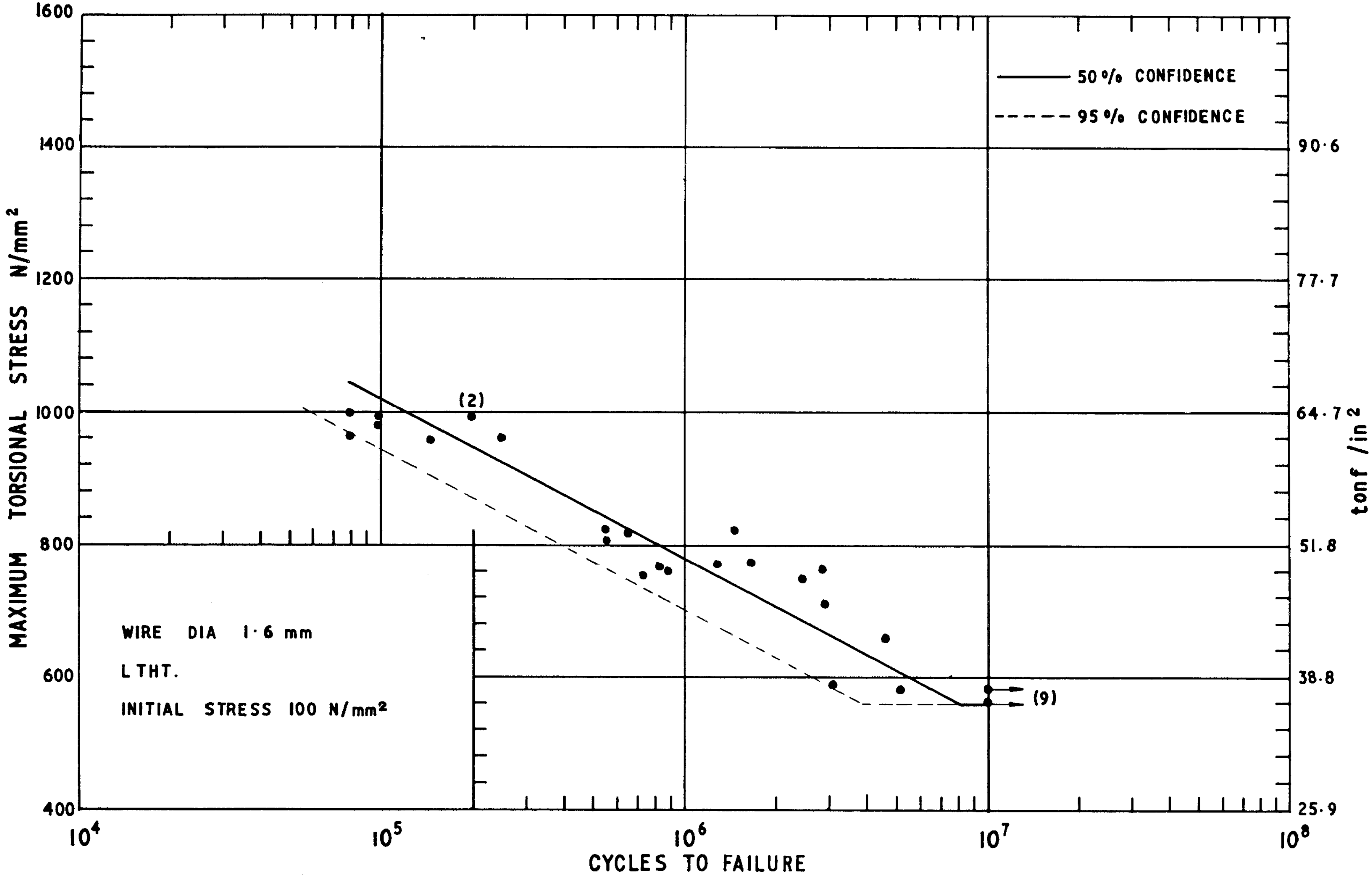

FIG.5 S/N CURVE FOR F.V. 520 (S) UNPEENED SPRINGS.

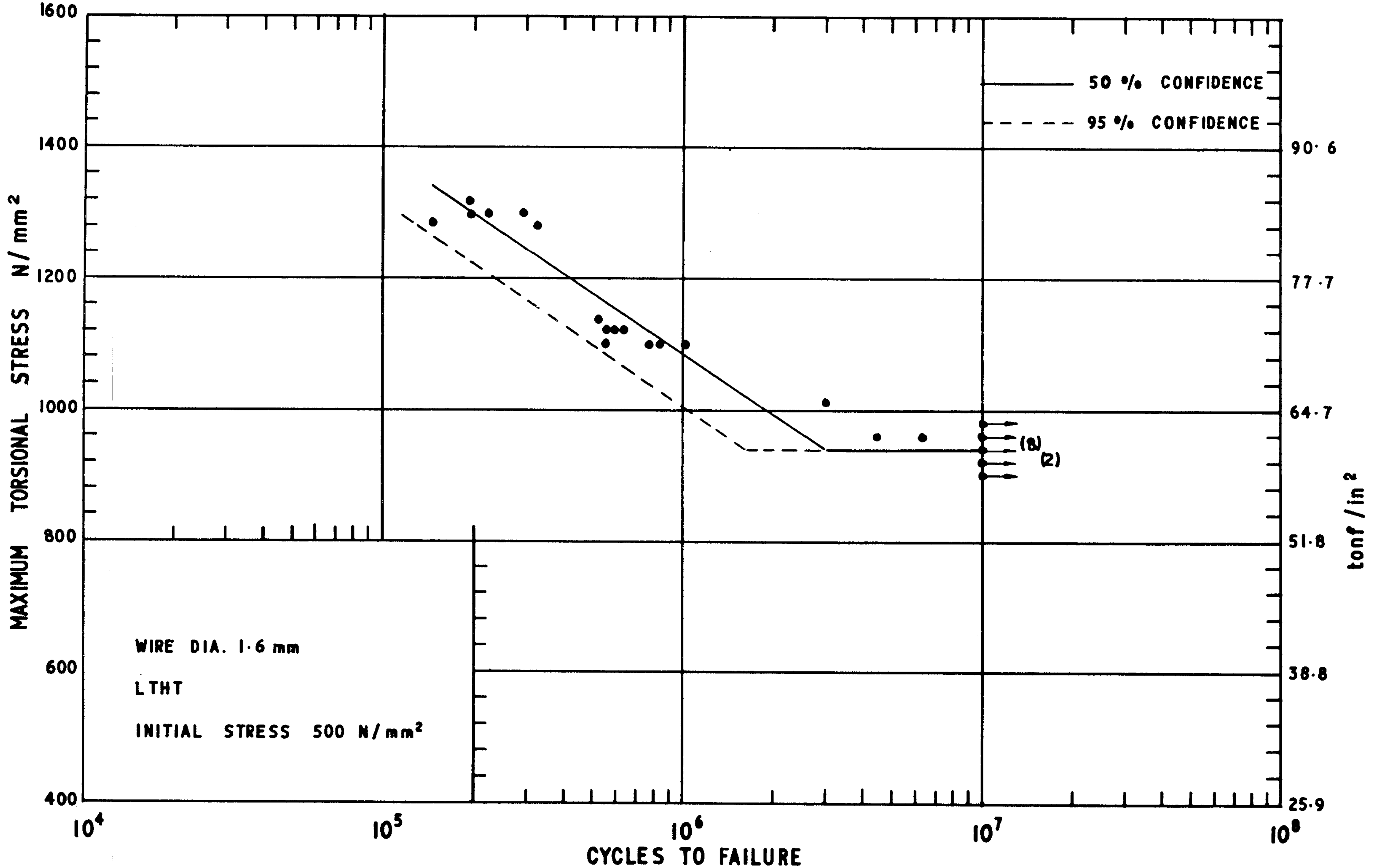

FIG.6. S/N CURVE FOR F.V. 520 (S) UNPEENED SPRINGS.

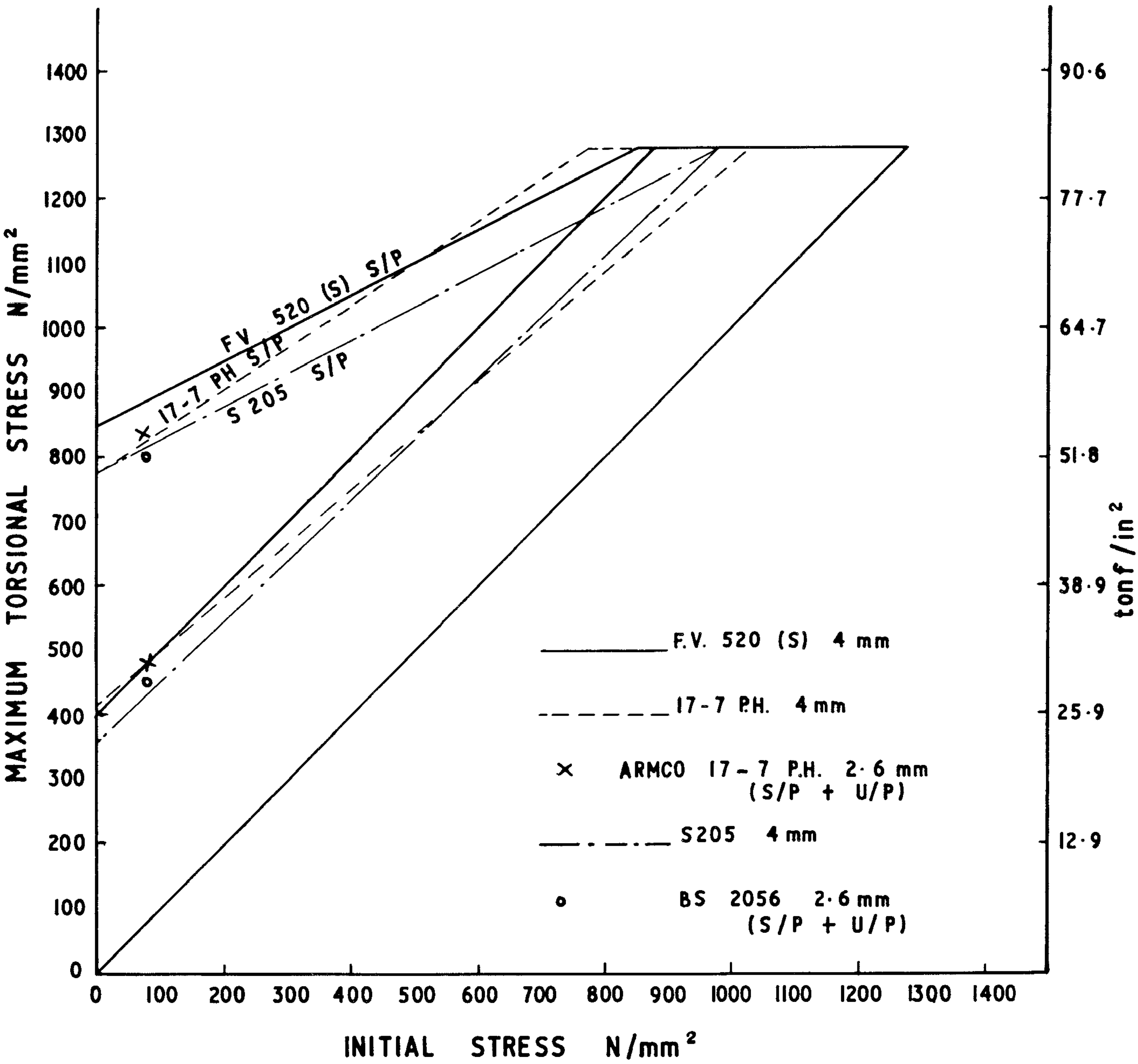

FIG. 7 MODIFIED GOODMAN DIAGRAMS FOR 10^7 CYCLES.

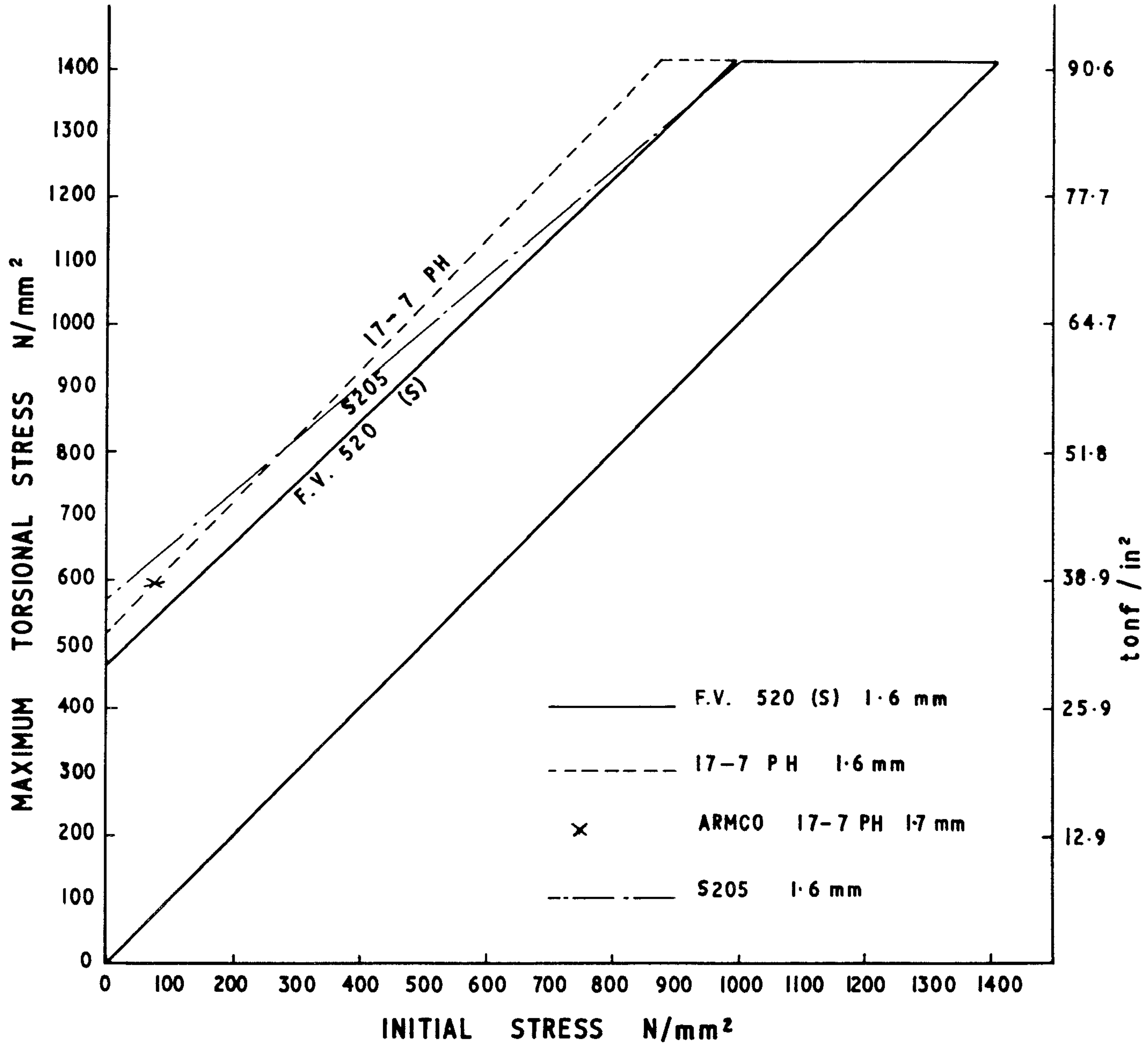

FIG. 8 MODIFIED GOODMAN DIAGRAMS FOR UNPEENED SPRINGS 10^7 CYCLES.

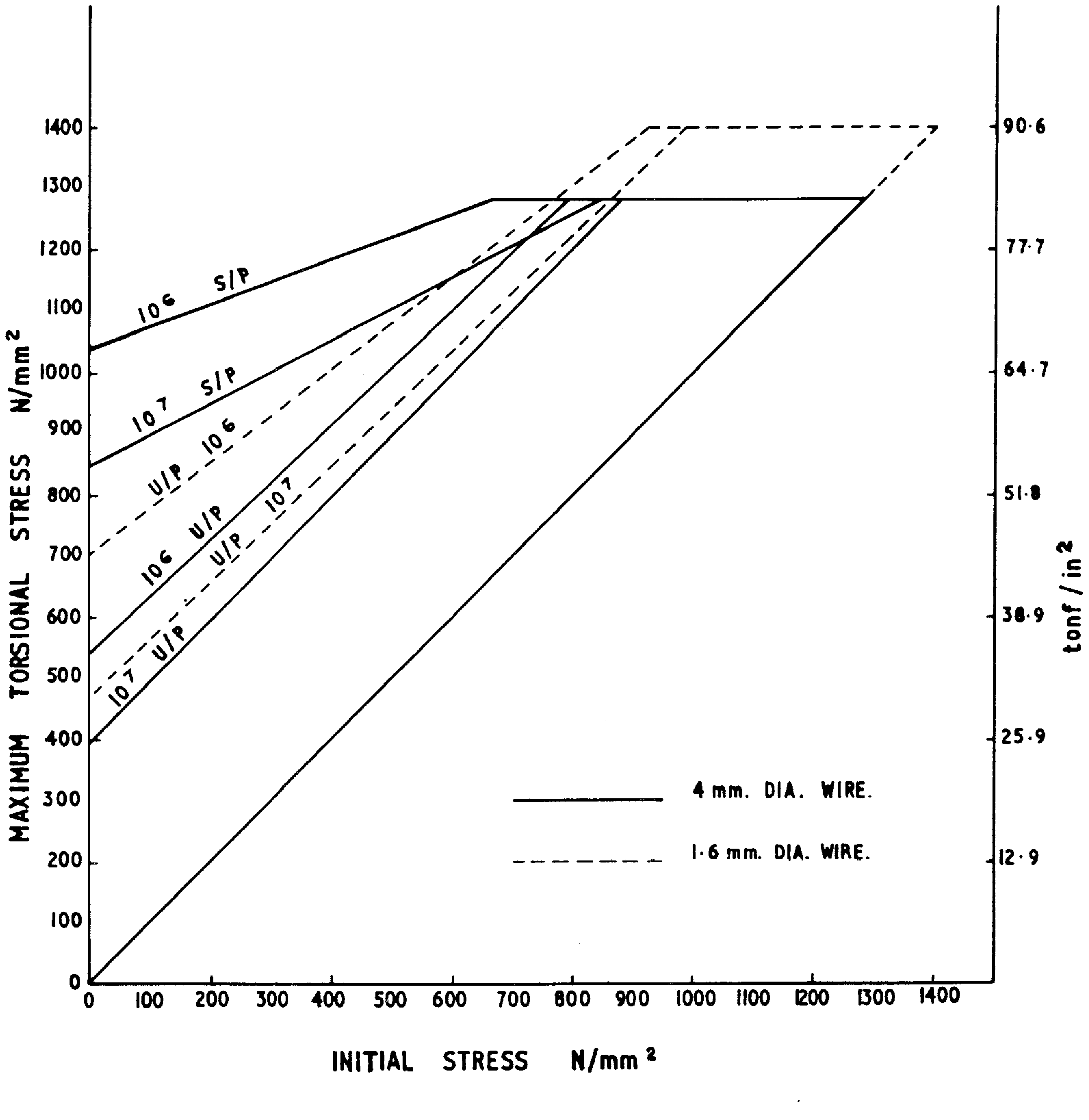

FIG. 9. MODIFIED GOODMAN DIAGRAMS FOR F.V. 520 (S) WIRE.

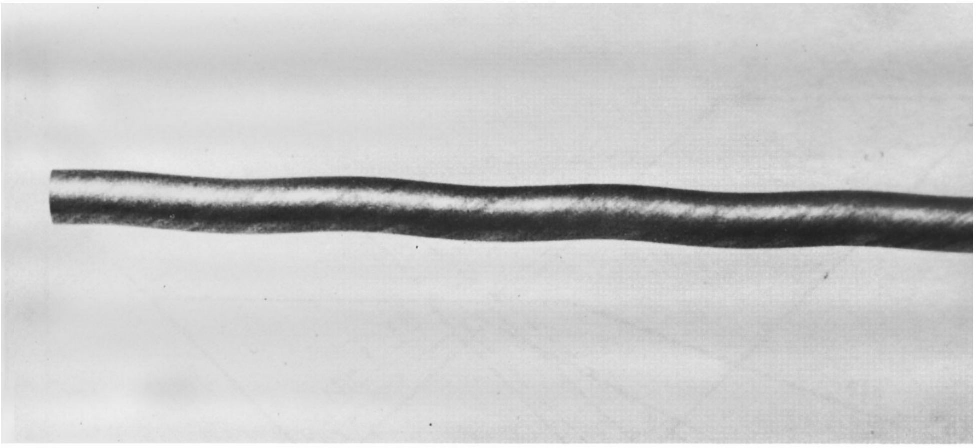

FIG. 10a x2

AUSTENITIC STAINLESS STEEL WIRE SHOWING A 'TOP-HAT' TORSION FAILURE (GOOD)

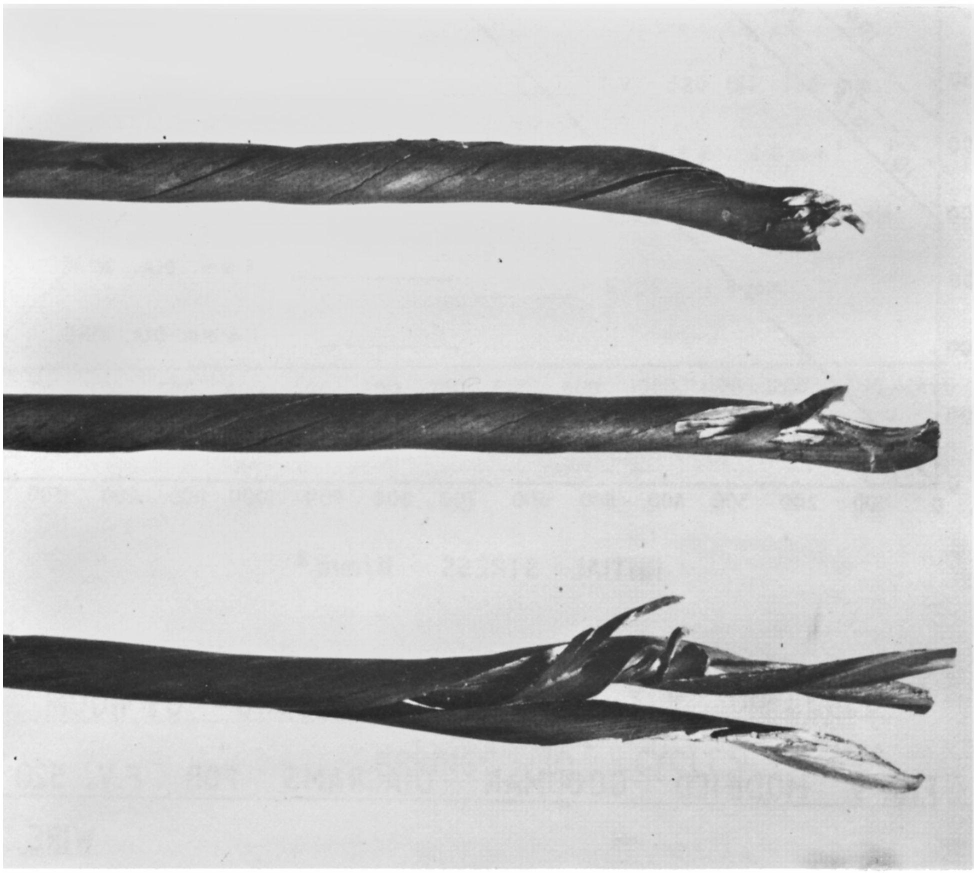

FIG. 10b x2

F.V. 520(S) WIRE SHOWING SEVERE DELAMINATION (BAD)