THE FATIGUE AND ASSOCIATED MECHANICAL PROPERTIES OF HELICAL COMPRESSION SPRINGS MANUFACTURED FROM S205 SPRING WIRE

(Contract No. K43A/65/CB 43A2)

Progress Report No. 4

by

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

Report No. 206

(August 1972)

THE SPRING RESEARCH ASSOCIATION

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SUMMARY

Fatigue tests have been carried out on springs manufactured from three batches of 4 mm and 1,6 mm diameter S205 quality spring wire, supplied by three separate wire manufacturers who for the purpose of identification are called Suppliers A, B and C. Testing included the response to shot peening of springs made from 4 mm diameter wire, together with the performance of springs at high stress levels, working close to the solid stress. Additional information was also obtained on the effect of spring index on fatigue life of unpeened springs manufactured from 4 mm diameter wire.

S/N curves have been produced for various initial stress levels, enabling the construction of modified Goodman diagrams.

In general springs manufactured from 4 mm diameter wire possessed similar fatigue properties in the unpeened condition, however, a large variation in fatigue strength was observed after shot peening, with springs manufactured from Supplier C revealing the best fatigue properties.

The maximum response to shot peening was observed at zero initial stress with all suppliers providing approximately 100 per cent increase in fatigue strength.

Comparisons made with springs manufactured from related specifications revealed the superior S205 shot peened springs to be inferior to those made from 17-7 PH material, this situation becoming more acute the higher the stress level. Shot peened springs manufactured from Armco 17-7 PH and B.S. 2056 quality wire showed very similar properties to S205 springs, at low initial stress levels.

S205 springs manufactured from three sources of 1.6 mm diameter wire, showed supplies A and B to have identical fatigue properties, with C revealing considerably better results, comparable to springs made from 17-7 PH wire.

(August 1972)

CONTENTS

Page No.

CONTENTS (Cont.)

Page No.

8. Tables

CONTENTS (Cont.)

10. Figures

CONTENTS (Cont.)

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1. INTRODUCTION

Stainless steels are the most expensive of the conventional steel qualities used by the spring maker, however, under certain climatic conditions, chemical environments, and elevated temperatures, the need for such steels is absolutely necessary. The most widely used stainless steels are the high chromium-nickel type which have a stable structure consisting essentially of a uniform gamma solid solution, and consequently these steels cannot be hardened by any form of heat treatment, quenching from 1000-1100°C merely softens them, and this treatment is used to obtain optimum resistance to corrosion. The only method of increasing the strength or more important the limit of proportionality and at the same time retaining sufficient ductility is to strain harden the material by cold working, followed by a suitable low temperature heat treatment. It is well known that austenitic stainless steel wire tends to give difficulty in spring making due to irregularity of forming behaviour, which can directly influence the mechanical and fatigue properties of wire and springs.

With this view in mind, the current programme was designed to examine in more detail the variations in static and dynamic properties of S205 stainless steel wire, and in doing so, extending the current programme of work, initiated by the

Ministry of Defence (Aviation)(1)(2)(3). Material ordered to the same S205 specification was obtained from three different wire manufacturers A, B and C and the mechanical and fatigue properties were obtained for each batch which involved testing 4 mm and 1.6 mm diameter wire. Additional tests have also been carried out to examine the response to shot peening of springs made from 4 mm diameter wire, together with the effect of spring index on the fatigue properties of unpeened springs made from 4 mm diameter wire.

2. MATERIAL

2.1 Wire

Wire manufactured to specification S205 was supplied in two sizes, i.e. 4 mm (0.160 in) and 1.6 mm (0.064 in) diameter, both in the as-drawn condition. Three separate sources of wire were utilised and Table I shows the chemical analysis of each of the six batches of wire supplied, these can be compared with the specification chemical analysis in Table II.

Although confirmation of the production processes for each of the batches was not available, in general wires drawn to these diameters, are normally given a final 50-60% reduction to 4 mm diameter and 75% reduction in area after an inter anneal for 1.6 mm diameter wire.

2.2 Springs

Design details of the two types of springs tested are outlined in Table III. Table IV shows the details of springs made from 4 mm diameter, used in an additional exercise to determine the effect of spring index on fatigue resistance of unpeened springs. Coiling of wire was carried out in the as-drawn condition, springs made from 4 mm diameter wire were hand coiled compared with the smaller springs which were made on an automatic spring coiling machine. Both coiling methods were found to be adequate for all the materials although galling occurred at one stage where there was an absence of lubrication. All the springs were low temperature heat treated in an air circulating furnace at 450°C for two hours, to gain the optimum increase in spring properties, as determined in previous work carried out by The Spring Research Association(4). 4 mm springs which were to be tested in the shot peened condition were peened to an Almen Arc rise of 0.018/0.022 A_2, followed by a second low temperature heat treatment of 220°C for ½ hour.

The entire consignment of shot peened and unpeened springs were then prestressed by loading to solid a sufficient number of times; until a constant length was achieved.

3. EXPERIMENTAL PROCEDURE

3.1 Fatigue Testing

Load tests were carried out on the springs to establish the necessary fatigue machine strokes to give the required stress ranges. All fatigue testing was carried out on forced motion multiple spring testing machines with a maximum available stroke of 25.4 mm (as shown in a previous progress report(2)).

Initial stress levels utilised in this programme varied according to ultimate requirements and are discussed below:-

3.2 Production of Fatigue Diagrams

For each source of supply and wire size S/N curves were obtained for unpeened springs at two initial stress levels, i.e. 100 and 500 N/mm^2 (6.5 and 32.4 tonf/in^2). Additional tests on the larger 4 mm diameter wire were repeated in the shot peened condition, thus producing two S/N curves for each wire size and surface condition.

Subsequently by extracting the relevant data from the S/N curves, modified Goodman diagrams were obtained.

3.2.1 Effect of Spring Index

The effect of spring index on the fatigue resistance of springs manufactured from 4 mm diameter wire was obtained, utilising material from Supplier B. Twenty springs for each of three indices were tested using an initial stress level of 100 N/mm^2 (6.5 tonf/in^2) and a maximum stress level of 700 N/mm^2 (45.3 tonf/in^2).

3.2.2 Performance at High Stress Levels

Additional fatigue tests with springs working close to the solid stress were also incorporated in the programme, using springs manufactured from 1.6 mm diameter wire, supplied by Source B. Testing stresses were so arranged that the initial stress level was never more than approximately 50% of the final stress, and the latter was not more than 90% of the solid stress; tests were so planned to enable fatigue testing to continue to 10^7 cycles. By utilising this method, one S/N curve was produced for an initial stress of 640 N/mm^2 (41.3 tonf/in^2).

3.3 Static Mechanical Testing

3.3.1 Tensile Testing

Tensile tests including full stress-strain data were obtained on both as-drawn and heat treated, 4 mm and 1.6 mm wire tak~~en fr~~om each of the three wire suppl~~iers.~~ All testing was carried out on a vertical Amsler testing machine equipped with an autographic stress-strain recorder.

3.3.2 Torsion Testing

Torsion testing was carried on a Tinius Olsen 84.7 N m capacity multi range, torsion testing machine, and on a vertical Amsler machine with a capacity of 5.6 N m, the latter was used for testing 1.6 mm diameter wire. In both cases stress-strain data in torsion were produced.

3.3.3 Reverse Bend and Wrapping Tests

Reverse bend and wrapping tests were carried out on wire samples taken from each of the three batches in accordance with specification S205 clauses 8.2 and 8.3.

4. RESULTS

Table I shows the chemical analyses of the wires tested, and these can be compared with the specification chemical analysis in Table II.

The appropriate results from broken springs were analysed statistically to provide the appropriate regression line for 50% and 95% confidence, and to determine the correlation coefficient.

The results of the fatigue tests are presented as S/N curves in Figs. 3 to 20, Fig. 21 showing the performance of springs working close to solid. The fatigue strengths for the various initial stress levels employed are plotted as modified Goodman diagrams in Figs. 22 and 23 and for ease of comparison the results are shown in Table V. Additional related data have also been included on the Goodman diagrams, and further details can be seen in Table VI.

Table VII shows the results obtained from testing three batches of 20 springs, with indices of 3, 7 and 10; the results are also plotted in Fig. 24.

Tables VIII and IX give the results obtained from tensile testing 4 mm and 1.6 mm diameter wires together with torsion data in Tables X and XI.

Figs. 25 and 26 show the variation in spring fractures obtained at high and low stress levels.

Figs. 27 and 28 show longitudinal sections of 4 mm and 1.6 mm diameter S205 quality wires etched in Marbles reagent.

5. DISCUSSION

5.1 The Effect of Carbon and Nickel on the Properties of Austenitic Stainless Steels

The magnitude of the resultant properties from cold working of stainless steel is largely dependent on the austenite stability of the material and therefore the chemical composition.

Investigations have been made to determine the minimum amounts of nickel which will ensure a stable structure with given contents of chromium. These values are affected to some extent by variations in carbon content, both those plotted in Fig. 1(5) relate to steels containing approximately 0.1%C; and it will be noticed that all the wire compositions in this report produce stable austenitic structures with the minimum contents being 18% chromium at approximately 7.5% nickel.

The higher the nickel content and the more stable the austenitic parent structure of the wire the softer and more ductile will this become after quenching from approximately 1100°C, and the lower the work hardening rate on subsequent drawing.

Karl-Heinz Kayser(6) has reported on the effect of nickel on the strain hardening of stainless steel wire, having undergone up to 97% deformation (0.9 to 0.15 mm diameter), and it was found that for a constant carbon content of approximately 0.08%, the ultimate tensile strength in general was reduced by 6% for a 2% increase in nickel content, (80% reduction in area).

Fig. 2(6) compares the effect of both nickel and carbon on the strain hardening of stainless steel and it will be observed that an increase of 0.08%C produces the same rise of work hardening as a constant carbon content of 0.08% accompanied by a loss of nickel from 13 to 8.2%.

Since the nickel content of all the materials tested are constant at approximately 8.3%, the carbon content variation would be the most influential factor producing up to a 10% variation in U.T.S., for a given reduction in area.

5.2 Fatigue Properties

5.2.1 Fatigue Strength of Springs Made from 4 mm Diameter Wire

In order to present conventional modified Goodman diagrams in this report, graphs have been extrapolated beyond the experimental point, however, all discussions and conclusions will be confined to the area on the graphs covered by experimental data.

It can be seen from examination of the modified Goodman diagrams in Fig. 22, that all the unpeened S205 springs possessed very similar fatigue properties, falling slightly below the properties for unpeened springs made from 4 mm diameter 17-7 PH wire. Springs made from Armco 17-7 PH wire showed a very high fatigue resistance, at low initial stress levels, whereas springs made from B.S. 1056 and Sandvik wire, showed similar properties to the springs under investigation.

Shot peening of S205 springs produced marked increases in fatigue strength ranging from 93 to 115% at zero initial stress level, the three supplies still maintaining an identical order of superiority to unpeened springs, i.e. C, B and A.

In comparing the above data with equivalent shot peened springs made from related wire, as shown in Fig. 22 and Table VI, it can be seen that the superior springs made from Source C had similar properties to springs made from 17-7 precipitation hardened wire at low initial stress levels, but became progressively inferior as the initial stress was increased. Springs manufactured from Armco 17-7 PH and B.S. 2056 wire again showed similar properties at very low initial stress levels, (lack of information prevented comparisons to be made at higher stresses).

The variation in response to shot peening of S205 springs can only be attributed to one or a combination of the following factors:-

1. Inconsistency in shot peening
2. Material condition
    - (a) Hardness
    - (b) Surface condition prior to peening
    - (c) Residual stress distribution
    - (d) Grain size

To ensure efficiency and consistency in shot peening, frequent tests are carried out on the SRA shot peening plant and suitable adjustments made when necessary. Hence the problem of inconsistency in peening between batches of springs should be negligible. Examination of the other factors calls for a programme of work which is outside the scope of the present exercise.

5.2.2 Fatigue Strength of Springs made from 1.6 mm Diameter Wires

From examination of the modified Goodman diagrams in Fig. 23 it can be observed that unpeened springs made from source C possessed the best fatigue properties at all initial stress levels, with A and B batches having identical properties, 80 to 120 N/mm^2 lower than C.

As observed previously with the larger springs, 17-7 PH springs showed slight inferiority at low initial stress levels, compared with batch C but proved to be far better at initial stress levels above about 250 N/mm^2. Springs made from Armco 17-7 PH wire had intermediate properties, whereas the Sandvik material again proved to be the most inferior.

5.2.3 Effect of Spring Index

Table VII outlines the results obtained from testing three batches of unpeened springs with indices of 3, 7 and 10. From the mean values it can be seen that increasing the spring index from 3 to 10, reduced the fatigue life of springs by approximately 60%, Fig. 24. In order to determine the significance of the results obtained, the Welch-Test(7) was utilised to compare the significance between pairs of mean values for indices 3 to 10, 3 to 7 and 7 to 10. A 99% level of confidence was obtained between the above couples confirming the conclusion that decrease in spring index increases spring endurance.

This observed increase in fatigue life with decreasing spring index could be due to an error in the generally accepted value of the Wahl correction factor K. Correction factors were therefore calculated from the data presented in Figs. 24 and 9 as follows:-

Index	Corrected stress N/mm^2	Uncorrected stress N/mm^2
10	700	$700/K_{10} = 615$
7	700	$700/K_7 = 593$
3	700	$700/K_3 = 437$

where K_3, K_7 and K_{10} are the generally accepted values of the K correction factors for indices of 3, 7 and 10.

The mean measured lines corresponding to these indices are obtained from Fig. 24 and transposed to Fig. 9, hence enabling measured corrected stress values to be determined from this figure.

Index	Measured corrected stress N/mm^2
10	815
7	715
3	600

The above data assumes that the correction factor K for an index of 6.5 which was used for the construction of Fig. 9 is correct.

The correction factor K^1 as determined from this work is therefore:-

$$K^1 = \frac{\text{measured corrected stress}}{\text{Uncorrected stress}}$$

and has numerical values as follows:-

Index	K^1	K
10	$^{815}/_{615}$ = 1.32	1.13
7	$^{715}/_{593}$ = 1.23	1.2
3	$^{600}/_{437}$ = 1.37	1.6

More experimental evidence would be required before any recommendation regarding the modification of the K correction factor could be made.

Another factor which could influence the fatigue behaviour of low index springs is the cold work which they receive during the coiling process. It is proposed that a similar experiment to the one reported here be undertaken on annealed wire which is subsequently hardened and tempered since this would enable the effect of strain hardening to be eliminated.

5.2.4 Performance of Springs at High Stress Levels

Fig. 21 shows the results obtained when fatigue testing unpeened springs manufactured from 1.6 mm diameter S205 quality wire supplied by source B.

Under certain circumstances springs are required to work at very high stress levels close to solid which may cause coil clashing and ultimately induce premature failure.

From the results obtained (Fig. 21) it would appear that the amount of scatter is no more than that observed on other springs tested at 500 N/mm^2. If the fatigue limit determined at an initial stress of 640 N/mm^2 is transposed to the modified Goodman diagram, it can be seen that it represents only a marginal lowering of fatigue properties.

5.3 Examination of Spring Fractures in 4 mm Diameter Wire

The type and location of the fractures for all the three wires examined has been recorded; however at this stage it is not possible to draw conclusions from these data.

5.3.1 Supplier A

Failures of shot peened springs at high stress levels showed elongated type fracture zones as indicated in Fig. 25a From examination of the fractures it was difficult to determine the point of crack initiation, although there was sufficient evidence to show that the crack propagation could be simplified by dividing into two stages. A 45° crack propagating along a resultant tensile component of stress and secondly travelling in a longitudinal manner, such that stress required to travel along the longitudinal direction, was less than that required to continue along a suitably oriented slip system.

At low stress levels (high fatigue life) a characteristic short 45° helicoidal fracture was observed as is shown in Fig. 25b. Comparing the two extreme cases above in profile by taking silhouette pictures as shown in Figs. 25c and d a predominant step like fracture could be seen, which occurred approximately 30 to 50% of the way between commencement and completion of failure.

Examination of springs in the unpeened condition showed a slightly different pattern in that fractures occurring at all stress levels had a longitudinal appearance similar to highly stressed shot peened springs, although as observed previously this feather-like appearance became more pronounced at higher stress levels, Fig. 26a.

Close examination of the failure contours, showed the step-like formation as outlined previously to occur at 90° rather than 45°.

The most significant feature in comparing peened and unpeened springs was the consistency in the position of fracture which in 80% of the cases occurred $2^3/4$ coils from one end.

5.3.2 Supplier B

An absence of a step type crack propagation was prevalent at low and intermediate stress levels, however, this feature re-appeared at high levels.

Fractures in this case were found to be relatively short at all levels, see Fig. 26b.

Failures in 70% of the cases occurred $2^3/4$ coils from one end.

Similar fractures were observed in the unpeened condition with failures occuring $1\frac{1}{2}$ coils from one end.

5.3.3 Supplier C

Shot peened spring failures at both high and low stress levels were very similar to those described for Supplier A, although low stress level failures showed a smoother and cleaner fracture surface, Fig. 26d, with a more complex crack propagation at high stresses, Fig. 26c.

In the unpeened condition, spring failures were very similar to those found in 5.3.1.

In general, shorter and more difficult to resolve fractures were observed in this case than those previously examined, at high stress levels, with simpler and cleaner fractures at low levels.

Positions of fracture, were found to vary considerably, and thus no pattern could be detected.

5.4 Examination of Spring Failures in 1.6 mm Wire

5.4.1 Supplier A

As observed in the 4 mm springs, increasing the stress caused an increase in the length of the fracture zone. Although it was more difficult to interpret the failure pattern, it was possible to see a similar formation to that discussed previously in 4 mm wire.

Over 90% of the failures occurred approximately 2½ coils from one end.

5.4.2 Supplier B

All the fatigue failures were relatively short, but all contained the characteristic step like formation, with failure 1½ coils from one end.

5.4.3 Supplier C

As observed in the 4 mm diameter wire springs, longitudinal fracture zones were shorter than for Supplier A and with little consistency in failure position.

The general pattern in fatigue fractures, whether the spring is unpeened or shot peened, would appear to be as follows:

(a) High Stress - long elongated and complex fracture (short life)

(b) Low Stress - short smooth and simple fracture (high life)

Comparisons of S205 spring failures with those from springs made from 17-7 PH wire(3), are very interesting, for the exact opposite occurs, where failures at high stresses are characterised by short relatively simple fracture zones, and at low levels by elongated feather-like failures, and one could assume that the major contributing factor producing the difference in fractures is the inclusion content of 17-7 PH wire.

With steels free of stress raisers torsional fatigue crack initiation can develop on either of the two planes of maximum shear, i.e. parallel and at right angles to the axis of the wire, since the shear strength is much less than the tensile strength of the material. If on the other hand stress raisers, such as surface imperfections, inclusions etc., are present then the stress concentration factor produced influences the tensile component much more than it does the shear components with the result that a 45° tensile crack will develop and propagate(9). Likewise, in material not having inherent stress raisers the development of a longitudinal shear crack can lead to a stress concentration of such magnitude that the tensile stress predominates and further crack propagation occurs at 45° to the wire axis.

The fractures observed after fatigue testing at relatively high applied stresses were, in general, of the longitudinal shear type, in all probability the length of this crack being accentuated by the directional property of the drawn structure.

Fractures of springs subjected to relatively low applied stresses, on the other hand, were basically helicoidal in nature with the origin of failure occuring at 45° to the wire axis. The lack of a predominately longitudinal shear fracture, in this case, being due to the lower applied stress being insufficient to open up the directional structure.

5.5 Mechanical Properties

5.5.1 Tensile Strength

From an examination of the data in Tables VIII and IX for 4 mm diameter wire supplied by source A, after L.T.H.T. at 450°C for 2 hours, the ultimate tensile strength could be seen to increase from 1459 N/mm^2 (94.5 tonf/in^2) to 1634 N/mm^2 (105.8 tonf/in^2), an increase of 12%. This increase observed should have been transmitted to the proof stresses, for when examining the tensile properties, a high elasticity is more important than U.T.S., and in fact the following increases in 0.1, and 0.2% proof stresses were noted, 20 and 12%.

An ultimate tensile strength of 1206 N/mm^2 (78.1 tonf/in^2) was recorded for Supplier B, with an increase to 1325 N/mm^2 (85.8 tonf/in^2) on L.T.H.T., an increase of 10% placing this wire well below the actual specification range of 1390 to 1590 N/mm^2 (90 to 103 tonf/in^2).

The effect of heat treatment on the proof stresses appeared more effective producing increases of 25, 15 and 10% for 0.1, 0.2 and 0.5% P.S.

An increase of 4% on the U.T.S. was recorded for material supplied by source C, after L.T.H.T., placing this material well within the required specification range. However, very disappointing increases were noted for the 0.1 and 0.2% proof stresses, these being of the order of 2% only.

Examination of the reduction in area figures showed the materials from suppliers A and B to have similar increases of 20 and 22% followed by C with 12% after low temperature heat treatment.

A comparison of the as-drawn and low temperature heat treated 1.6 mm diameter wires indicated that all of the three batches conformed to tensile specification requirements, with Supplier A showing a 16% increase followed by Supplier B and C with 13 and 8% respectively.

Comparison of the 0.1% PS values showed the opposite of the above, with Supplier C now only revealing a mere 2% increase, as opposed to approximately 15% with A and B.

In all cases wire from Supplier C showed the smallest response to low temperature heat treatment; however this **material produced springs with superior fatigue properties.**

Increases in elastic properties of wire have been shown to occur due to stress relief(10), and since material C produced a low response to L.T.H.T., it can be assumed that residual stresses were relatively low.

5.5.2 Fatigue Ratios

From examination of the results (Table XII) it can be seen that for unpeened springs manufactured from 4 mm diameter wire, supply B had the best fatigue ratio of 0.28, followed by C at 0.24, and A at 0.20. However, after peening Suppliers B and C produced an identical ratio of 0.52, with A at 0.37.

Examining 1.6 mm wire, the ratios were relatively constant at 0.28, 0.29 and 0.32 for Suppliers A, B and C respectively.

The ratios obtained in general were very similar to those for springs manufactured from 17-7 PH spring wire(3).

5.5.3 Torsional Strength

It can be seen in Tables X and XI that 4 mm wire from Supplier A revealed an increase of 7% after LTHT, producing a maximum shear stress of 1214 N/mm^2 (78.6 tonf/in^2). Suppliers A and B revealed similar increases of 6%, the highest value recorded being from Supplier C. More significant results can be detected by examining the change in proof stress data, confirming that the increase in torsional properties is more significant than in tensile. The 0.1% PS data produced increases of 19, 22 and 13% for A, B and C after LTHT. The 0.2% PS data revealed changes from 14% (A and C) to 26% (B) after LTHT.

The 1.6 mm diameter springs followed a similar pattern to 4 mm with increases in maximum shear stress of the order 5, 2 and 6% for A, B and C respectively. Large increases in 0.1% proof stress data were observed, the best value being with a 33% increase, similar to the 4 mm wire. The remaining qualities provided only 16 and 19% increases. However, as the proof stress was increased to 0.2% and 0.5% values of the order of 20% were obtained.

5.5.4 Torsional Fracture Characteristics of Wire

Visual observations of as-drawn and heat treated test pieces during testing revealed the characteristic non-uniform pattern of twisting from first to last turn. Early states of straining, within the first revolution, revealed uniform twisting, however, after two or three turns buckling was apparant but disappeared after further turns.

After approximately five revolutions localised twisting began to occur towards the centre of the gauge length, a further nine twists induced a second area of localised twisting and finally failure occurred with a smooth surface without spiral delamination and with an even fracture at right angles to the wire axis.

5.6 Metallographic Examination of Wire

5.6.1 4 mm Diameter Wire

5.6.1.1 Unetched Condition

Samples were taken from each of the supplied batches and mounted. Longitudinal and transverse sections were then examined microscopically, no signs of internal or surface defects were observed which could have influenced the mechanical or fatigue properties.

5.6.1.2 Etched Condition

The above mounted specimens were etched in Marbles reagent for a suitable period of time. Wire from Suppliers B and C showed very similar microstructures containing a relatively coarse but heavily distorted martensitic structure, Figs. 26b and 26c.

Wire from Supplier A, which produced the most inferior fatigue properties, revealed a very fine structure of distorted martensite, Fig. 26a. Austenite to martensite determinations revealed all the materials to contain approximately 100% martensite.

Intermediate heat treatments are very important when drawing 18/8 austenitic stainless wire, and this feature will no doubt have influenced the resultant grain size. However, further work would be necessary to monitor the effect of heat treatment on grain size and fatigue resistance.

5.6.2 1.6 mm Diameter Wire

Examination in the unetched condition revealed negative results and thus the samples were etched in Marbles reagent, Fig. 27. Material from source B and C again revealed similar 100% martensitic structures, with C being the coarser of the two. Here again supply A revealed the finest structure, but the most inferior fatigue properties.

6. CONCLUSIONS

1. Unpeened springs manufactured from 4 mm diameter S205 wire, in general revealed very similar fatigue properties, with springs from Supplier C being marginally better and comparable to 17-7 PH and B.S. 2056 unpeened springs.

2. A variation in response to shot peening was observed, all supplies revealing approximately 100% increase in fatigue strength at zero initial stress.

3. The best shot peened S205 springs were inferior to equivalent springs made from 17-7 PH wire. Those made from Armco 17-7 PH and B.S. 2056 showing similar properties to the above S205 springs at low initial stress levels.

4. Of the S205 springs made from 1.6 mm diameter wire, those from Supplier C possessed the most superior properties, comparable to 17-7 PH and Armco 17-7 PH springs.

5. Springs tested at high stress levels, working close to the solid stress, showed reliable data, thereby indicating high working stressing to be a practical proposition.

6. Testing of unpeened springs made from 4 mm diameter wire, with indices of 3, 7 and 10, showed a significant reduction in fatigue life from 3 to 10, of approximately 60%.

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TABLE I CHEMICAL ANALYSES OF S205 QUALITY WIRES

SUPPLIER	WIRE DIAMETER	%C	%Si	%Mn	%S	%P	%Ni	%Cr
A	4 mm	0.05	0.50	1.40	0.018	0,023	8,22	18.24
	1,6 mm	0.04	0,43	1.60	0,023	0.029	8.26	17.94
B	4 mm	0.09	0,35	0,62	0,011	0,014	8.30	17,70
	1.6 mm	0.09	0,35	0.62	0,011	0.014	8,30	17,70
C	4 mm	0,07	0.47	0.69	0,008	0,009	8,30	17,70
	1.6 mm	0,07	0,47	0.69	0.008	0.009	8,30	17.70

TABLE II SPECIFICATION CHEMICAL ANALYSIS

%C	%Si	%Mn	%S	%P	%Ni	%Cr
0.15 Max	0.2-1.0	0.5-2,0	0.025 Max	0,035 Max	7.5-9.0	17,0-19.0

TABLE III

STANDARD SPRING DESIGN DATA

	4 mm WIRE		1.6 mm WIRE	
	METRIC	IMPERIAL	METRIC	IMPERIAL
SPRING MEAN DIAMETER	26.90 mm	1.05 in	11.00 mm	0.40 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	50.00 mm	2.00 in	22.00 mm	0.90 in
SOLID STRESS AFTER GRINDING AND PRESTRESSING	1282 N/mm^2	83.0 tonf/in^2	1429 N/mm^2	94.4 tonf/in^2

TABLE IV SPRING DESIGN DATA FOR VARIOUS INDICES

(4 mm DIAMETER S205 WIRE)

(SUPPLIER B)

INDEX	3	7	10
SPRING MEAN DIAMETER	12 mm	28 mm	40 mm
NO. OF ACTIVE COILS	9	2.5	1
TOTAL NO. OF COILS	11	4.5	3
FREE LENGTH AFTER GRINDING AND PRESTRESSING	67.4 mm	41.3 mm	35.4 mm
SOLID STRESS AND GRINDING AND PRESTRESSING	1400 N/mm^2	1400 N/mm^2	1400 N/mm^2
INDEX (C)	3	7	10
CORRECTION FACTOR (k)	1.60	1.20	1.13

TABLE V

FATIGUE DATA FOR SPRINGS MADE FROM S205 QUALITY WIRE

SUPPLIER	WIRE DIAMETER	SURFACE CONDITION	FATIGUE STRENGTH AT AN INITIAL STRESS OF:- 100 N/mm^2			500 N/mm^2		
			CYCLES TO FAILURE					
			10^5	10^6	10^7	10^5	10^6	10^7
A	4 mm (0.160 in)	Shot Peened	935	665	665	-	995	995
	4 mm (0.160 in)	Unpeened	815	400	400	-	780	780
	1.6 mm (0.064 in)	Unpeened	975	750	565	-	875	875
B	4 mm (0.160 in)	Shot Peened	1100	740	740	1240	1020	990
	4 mm (0.160 in)	Unpeened	815	440	440	1210	790	790
	1.6 mm (0.064 in)	Unpeened	-	610	580	1190 1315*	1050 1105*	890 1010*
C	4 mm (0.160 in)	Shot Peened	-	830	830	1320	1030	1030
	4 mm (0.160 in)	Unpeened	870	510	450	1130	830	830
	1.6 mm (0.064 in)	Unpeened	1000	650	650	1210	1030	990

* INITIAL STRESS 640 N/mm^2 (41.3 tonf/in^2)

TABLE VI COMPARATIVE FATIGUE DATA FOR 10^7 CYCLES

MATERIAL	WIRE DIAMETER (mm)	SURFACE CONDITION	FATIGUE LIMIT N/mm^2	INITIAL STRESS N/mm^2
17-7 PH	4.0	SHOT PEENED	840	100
17-7 PH	4.0	SHOT PEENED	1100	500
17-7 PH	4.0	UNPEENED	500	100
17-7 PH	4.0	UNPEENED	750	400
17-7 PH	1.6	UNPEENED	620	100
17-7 PH	1.6	UNPEENED	1025	500
ARMCO 17-7PH	2.6	SHOT PEENED	840	77
ARMCO 17-7PH	2.6	UNPEENED	590	77
ARMCO 17-7PH	1.7	UNPEENED	590	77
BS 2056	2.6	SHOT PEENED	800	77
BS 2056	2.6	UNPEENED	450	77
SANDVIK (18-8)	4.0	UNPEENED	440	100
12 RIO	4.0	UNPEENED	680	500
SANDVIK	2.0	UNPEENED	530	100
12 RIO	2.0	UNPEENED	720	400

TABLE VII FATIGUE DATA FOR UNPEENED SPRINGS MADE FROM 4 mm (0.160 in) DIAMETER S205 QUALITY WIRE (SUPPLIER B)

INITIAL STRESS 100 N/mm^2 (6.47 tonf/in^2)
MAXIMUM STRESS 700 N/mm^2 (45.3 tonf/in^2)

TEST NUMBER	CYCLES TO FAILURE (N)		
	SPRING INDEX		
	3	7	10
1	525 000	493 000	94 500
2	189 000	315 000	84 000
3	451 000	183 750	89 250
4	220 500	126 000	147 000
5	168 000	110 250	26 250
6	278 250	162 000	147 000
7	225 750	117 000	126 000
8	372 750	194 000	99 750
9	388 500	126 000	105 000
10	336 000	189 000	63 000
11	351 750	171 000	105 000
12	241 500	207 000	99 750
13	383 250	126 000	94 500
14	277 250	168 000	105 000
15	325 500	162 000	126 000
16	157 500	141 750	110 250
17	236 250	126 000	89 250
18	294 000	162 750	94 500
19	178 000	246 750	194 250
20	294 000	136 500	115 500
MEAN	278 600	170 100	99 540

TABLE VIII

TENSILE DATA FOR S205 QUALITY WIRES (AS-DRAWN)

SUPPLIER	WIRE DIAMETER	ULTIMATE TENSILE STRENGTH		PROOF STRESS						REDUCTION IN AREA %	ELONGATION % (2 in)
				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		
A	4 mm MEAN VALUE	1459	94.5	1050	68.0	1277	82.7	-	-	26.0	3.0
	1.6 mm MEAN VALUE	1660	107.5	1392	90.1	1615	104.6	-	-	27.3	2.0
B	4 mm MEAN VALUE	1206	78.1	814	52.7	973	63.0	1122	72.6	27.3	4.3
	1.6 mm MEAN VALUE	1603	103.8	1072	69.4	1265	81.9	1552	100.5	32.0	5.0
C	4 mm MEAN VALUE	1466	94.9	1126	71.3	1285	83.2	-	-	27.6	2.3
	1.6 mm MEAN VALUE	1629	105.5	1376	89.1	1569	101.6	-	-	22.0	2.6

TABLE IX

TENSILE DATA FOR S205 QUALITY WIRES
(L.T.H.T. 450°C-2hrs)

SUPPLIER	WIRE DIAMETER	ULTIMATE TENSILE STRENGTH				PROOF STRESS						REDUCTION IN AREA %	ELONGATION % (2")
		SPECIFIED		ACTUAL		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	$tonf/in^2$	N/mm^2	$tonf/in^2$		
A	4 mm MEAN VALUE	1400/1600	90/103	1634	105.8	1257	81.4	1430	92.6	1612	104.4	31.3	2.5
	1.6 mm MEAN VALUE	1750/1950	113/126	1800	116.6	1585	102.6	1730	112.0	-	-	26.5	3.0
B	4 mm MEAN VALUE	1400/1600	90/103	1352	85.8	1015	65.7	1120	72.5	1234	79.9	35.0	4.0
	1.6 mm MEAN VALUE	1750/1950	113/126	1802	116.7	1248	80.8	1490	96.5	-	-	25.0	3.0
C	4 mm MEAN VALUE	1400/1600	90/103	1521	98.5	1101	72.9	1311	84.9	1480	95.8	31.0	2.0
	1.6 mm MEAN VALUE	1750/1950	113/126	1897	122.8	1409	91.2	1637	106.0	1882	121.9	36.0	2.0

TABLE X TORSION DATA FOR AS-RECEIVED S205 QUALITY WIRES (100d)

SUPPLIER	WIRE DIAMETER	MAXIMUM SHEAR STRESS		PROOF STRESS					
				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	$tonf/in^2$
A	4 mm MEAN VALUE	1140	73.8	579	37.5	686	44.4	-	-
	1.6 mm MEAN VALUE	1126	72.9	649	42.0	751	48.6	936	60.6
B	4 mm MEAN VALUE	1114	72.1	541	34.9	653	42.3	757	49.0
	1.6 mm MEAN VALUE	1206	78.1	607	39.3	727	47.1	879	56.9
C	4 mm MEAN VALUE	1198	77.6	592	38.3	715	46.3	-	-
	1.6 mm MEAN VALUE	1205	78.0	633	41.0	735	47.6	939	60.8

TABLE XI TORSION DATA FOR S205 QUALITY WIRES (L.T.H.T. 450°C - 2hrs)

SUPPLIER	WIRE DIAMETER	MAXIMUM SHEAR STRESS		PROOF STRESS					
				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	$tonf/in^2$
A	4 mm MEAN VALUE	1214	78.6	687	44.5	826	53.6	-	-
	1.6 mm MEAN VALUE	1181	76.5	793	51.3	914	59.2	1120	72.6
B	4 mm MEAN VALUE	1138	73.6	656	42.5	822	53.2	-	-
	1.6 mm MEAN VALUE	1177	76.2	806	52.2	868	56.2	1035	67.0
C	4 mm MEAN VALUE	1275	82.6	717	46.4	816	52.9	-	-
	1.6 mm MEAN VALUE	1134	73.4	692	44.8	851	55.1	1056	68.4

TABLE XII FATIGUE RATIOS OF S205 QUALITY WIRE

SUPPLIER	WIRE DIAMETER	SURFACE CONDITION	FATIGUE RATIO*
A	4 mm	S/P	0.37
		U/P	0.20
	1.6 mm	U/P	0.28
B	4 mm	S/P	0.52
		U/P	0.28
	1.6 mm	U/P	0.29
C	4 mm	S/P	0.52
		U/P	0.24
	1.6 mm	U/P	0.32

* Fatigue limit at zero initial stress divided by the U.T.S. after LTHT of 450°C/2h.

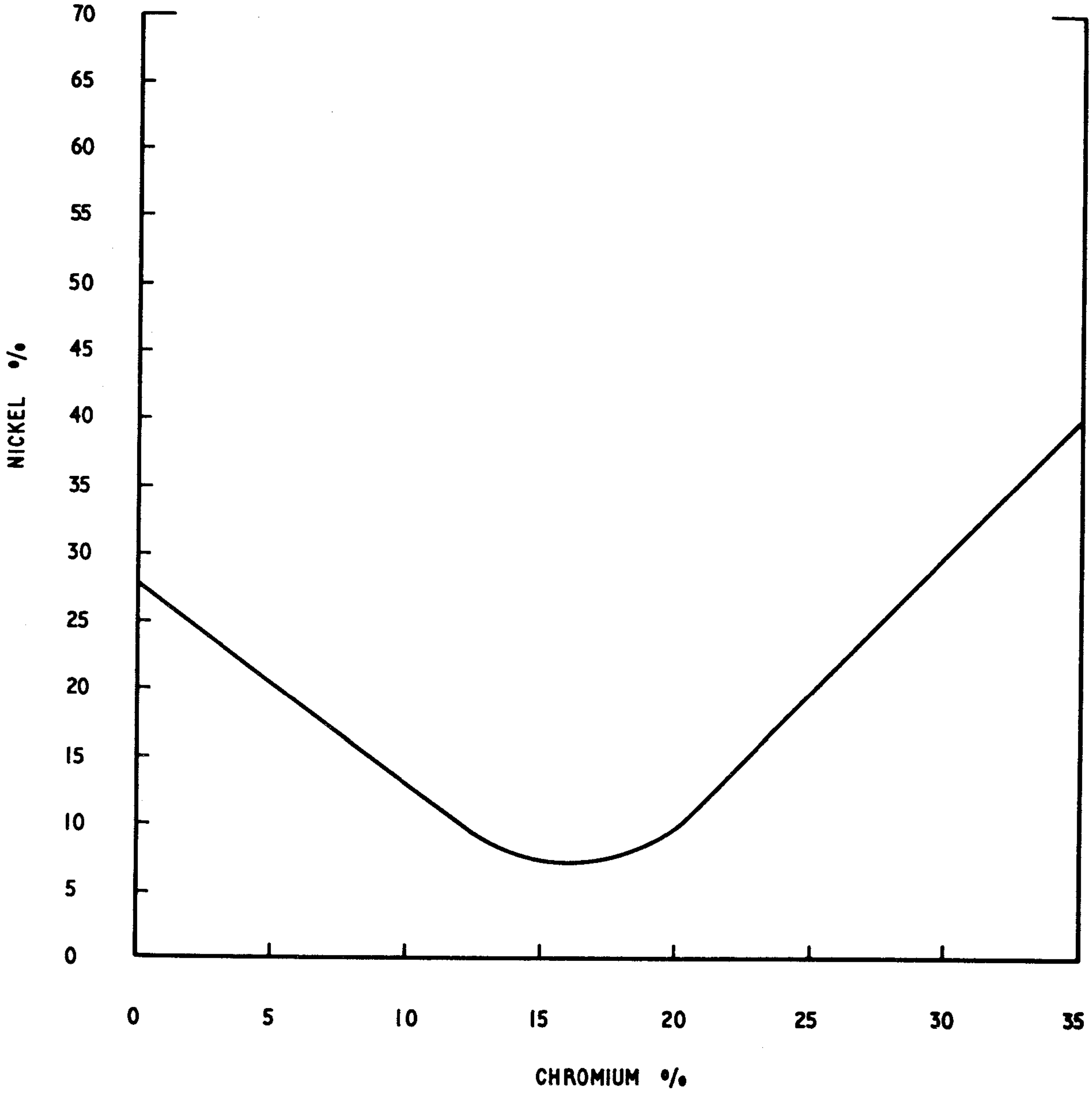


FIG.1. MINIMUM CONTENTS OF NICKEL NECESSARY TO OBTAIN A STABLE AUSTENITIC STRUCTURE WITH GIVEN CONTENTS OF CHROMIUM(5)

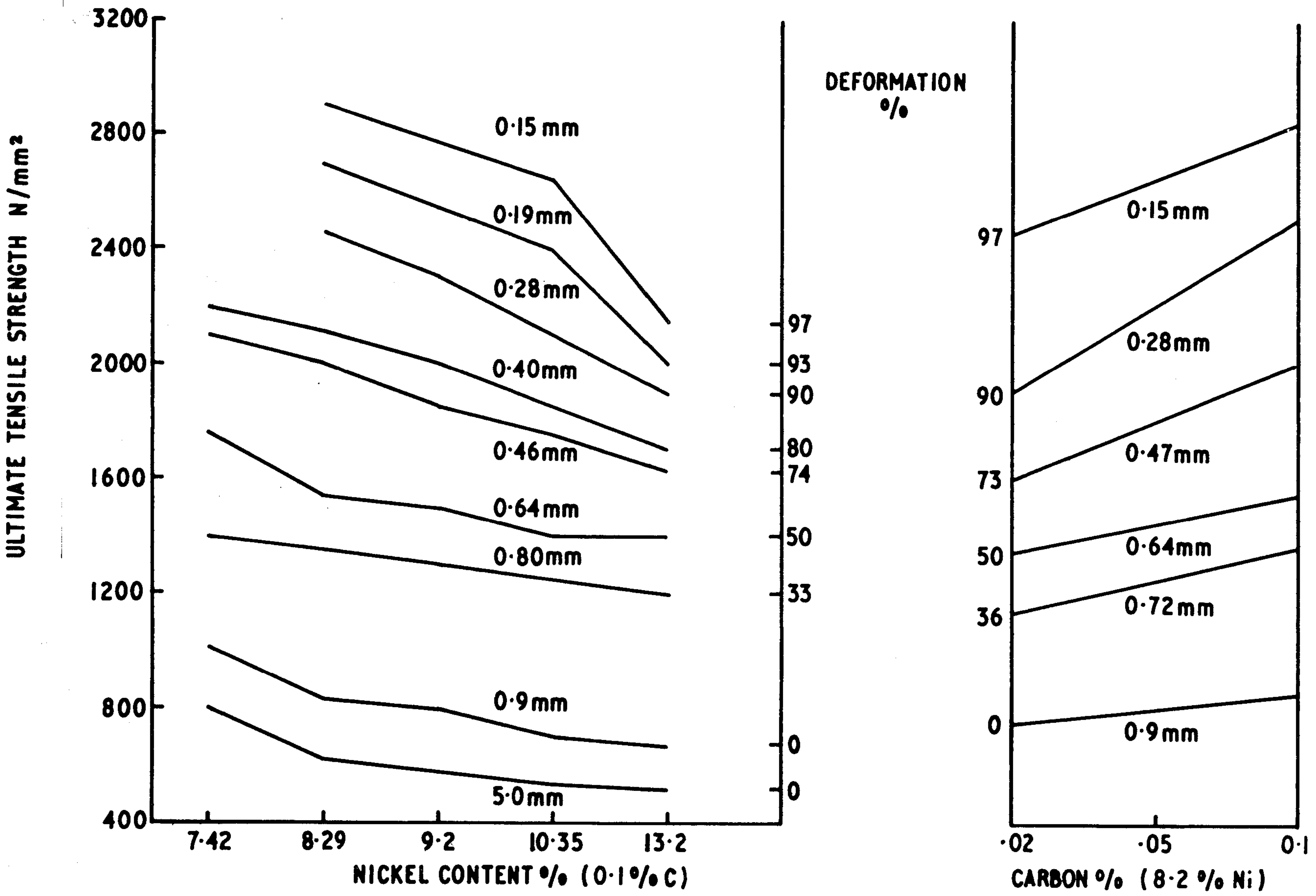


FIG. 2. THE EFFECT OF Ni AND C ON THE TENSILE STRENGTH OF AUSTENITIC STAINLESS STEEL WIRE.(6)

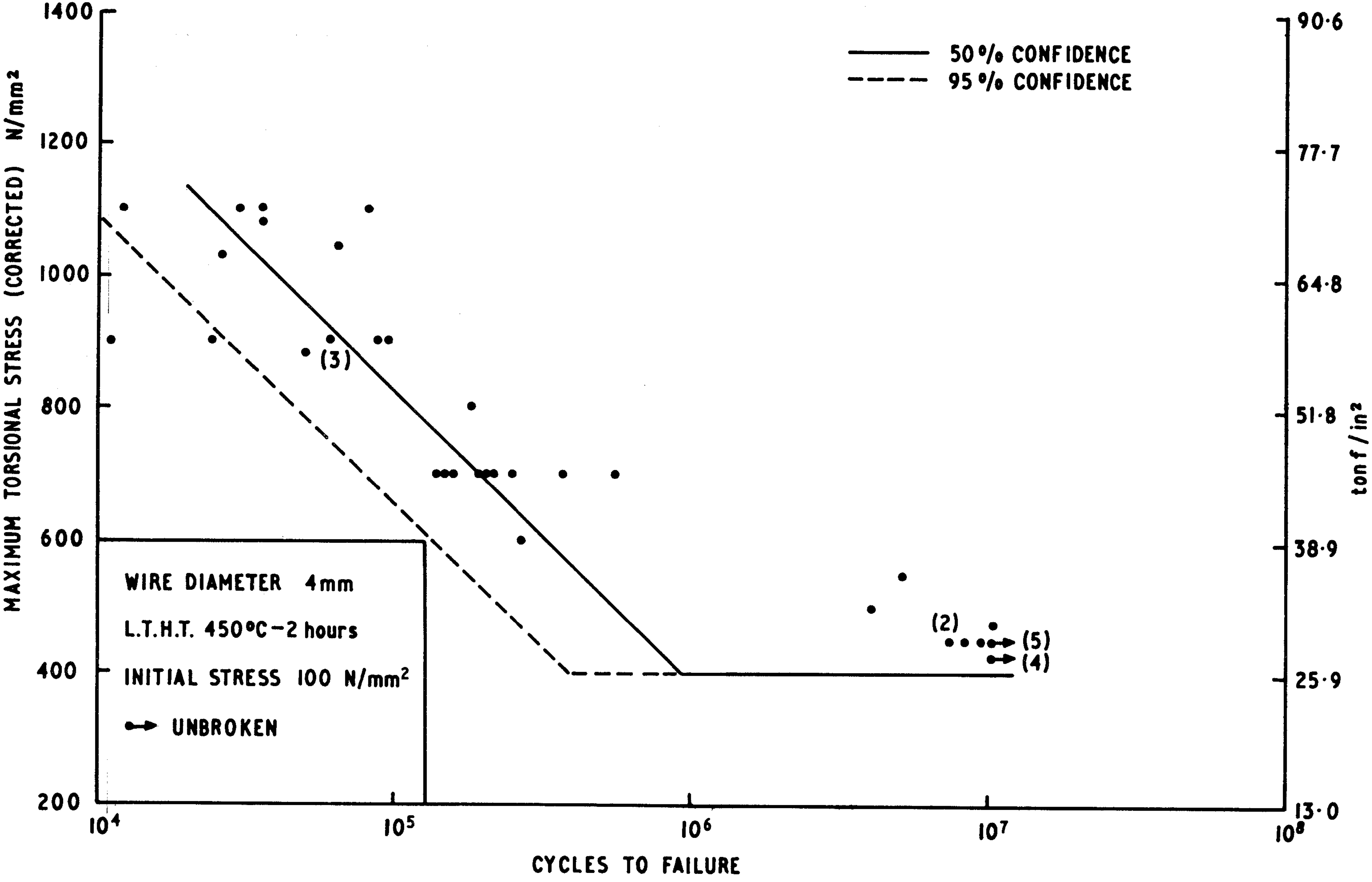


FIG. 3. S/N CURVE FOR S205 UNPEENED SPRINGS SUPPLIER A

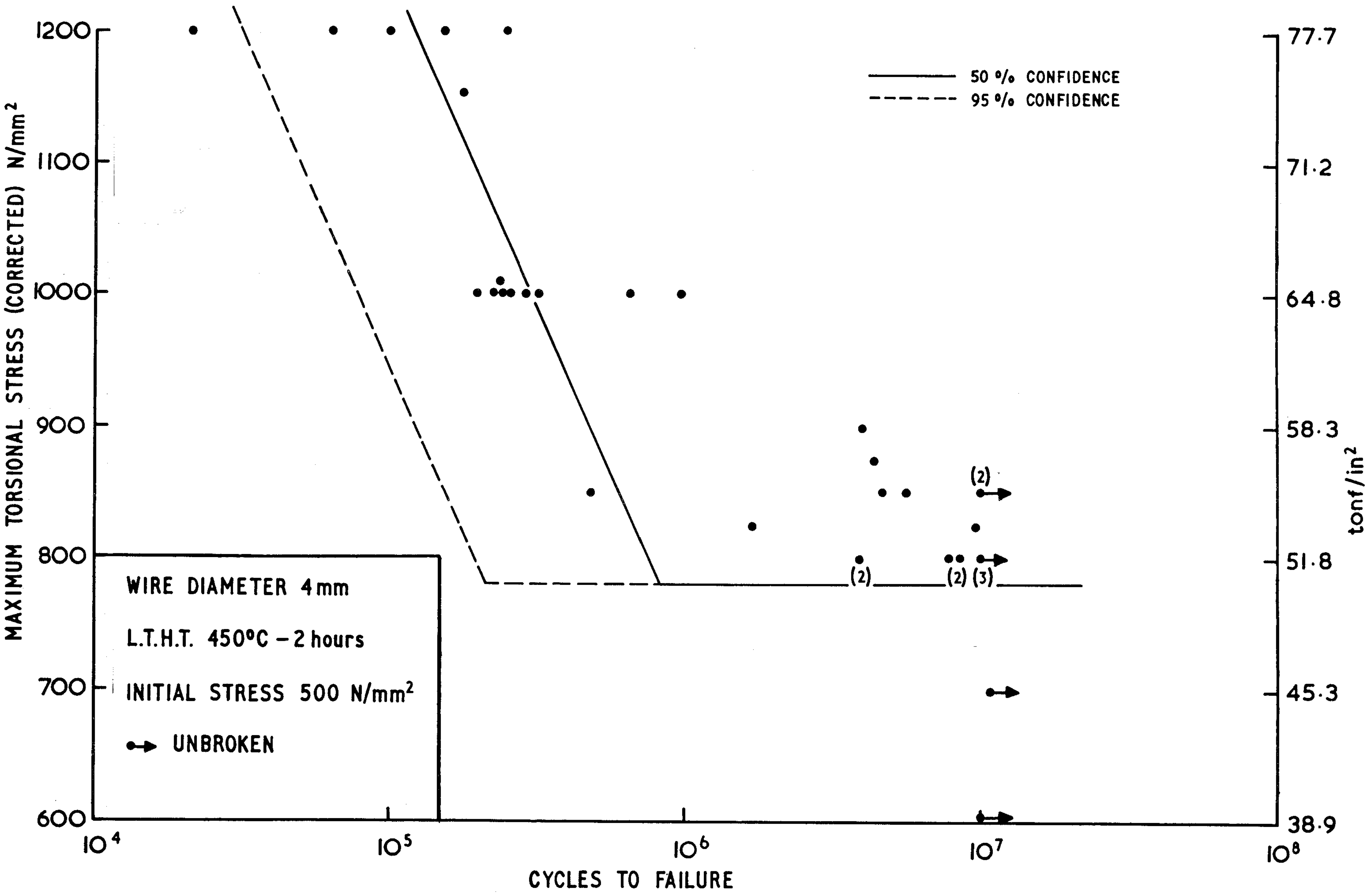


FIG.4 S/N CURVE FOR S205 UNPEENED SPRINGS SUPPLIER A

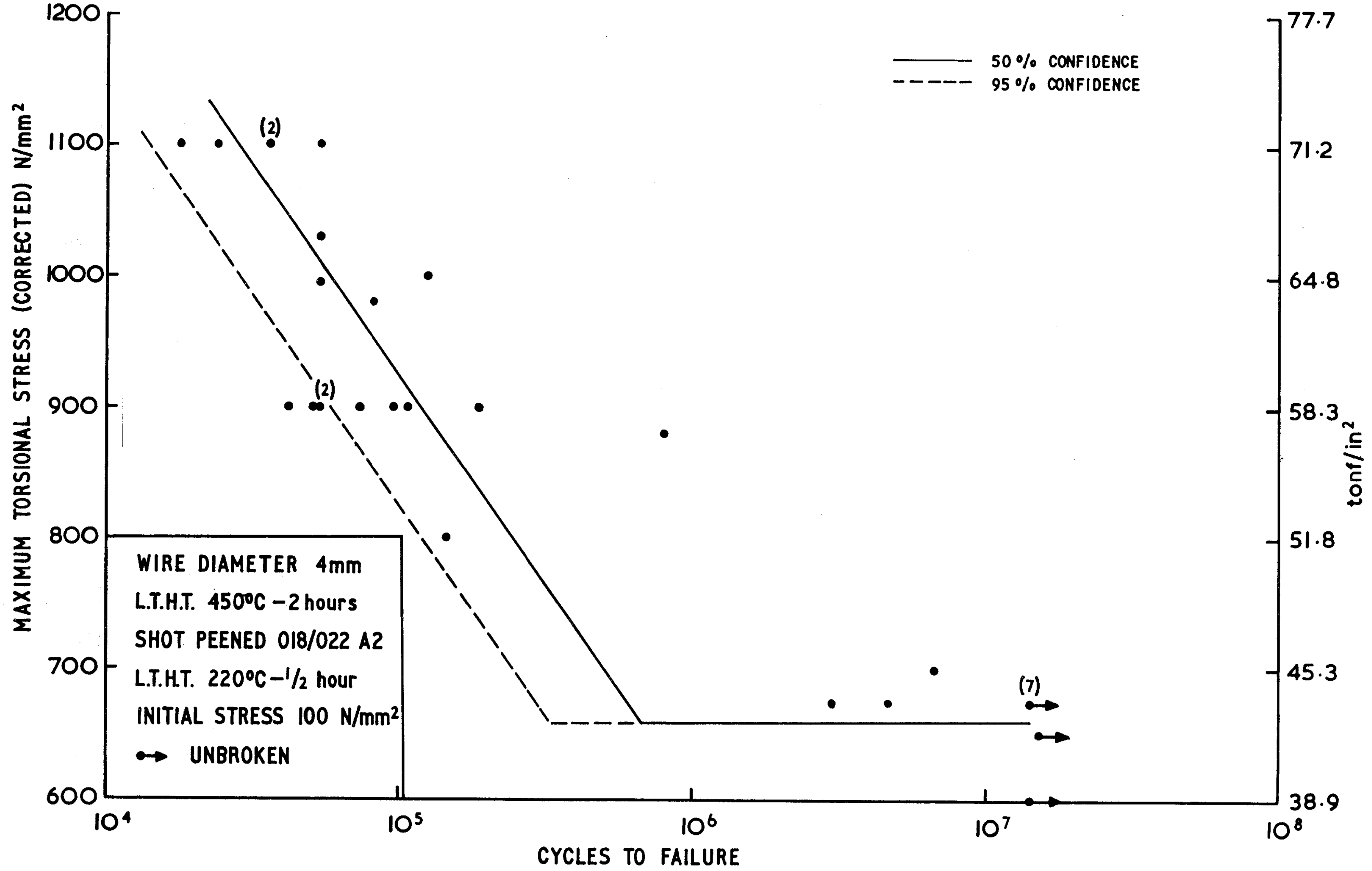


FIG.5 S/N CURVE FOR S205 SHOT PEENED SPRINGS SUPPLIER A

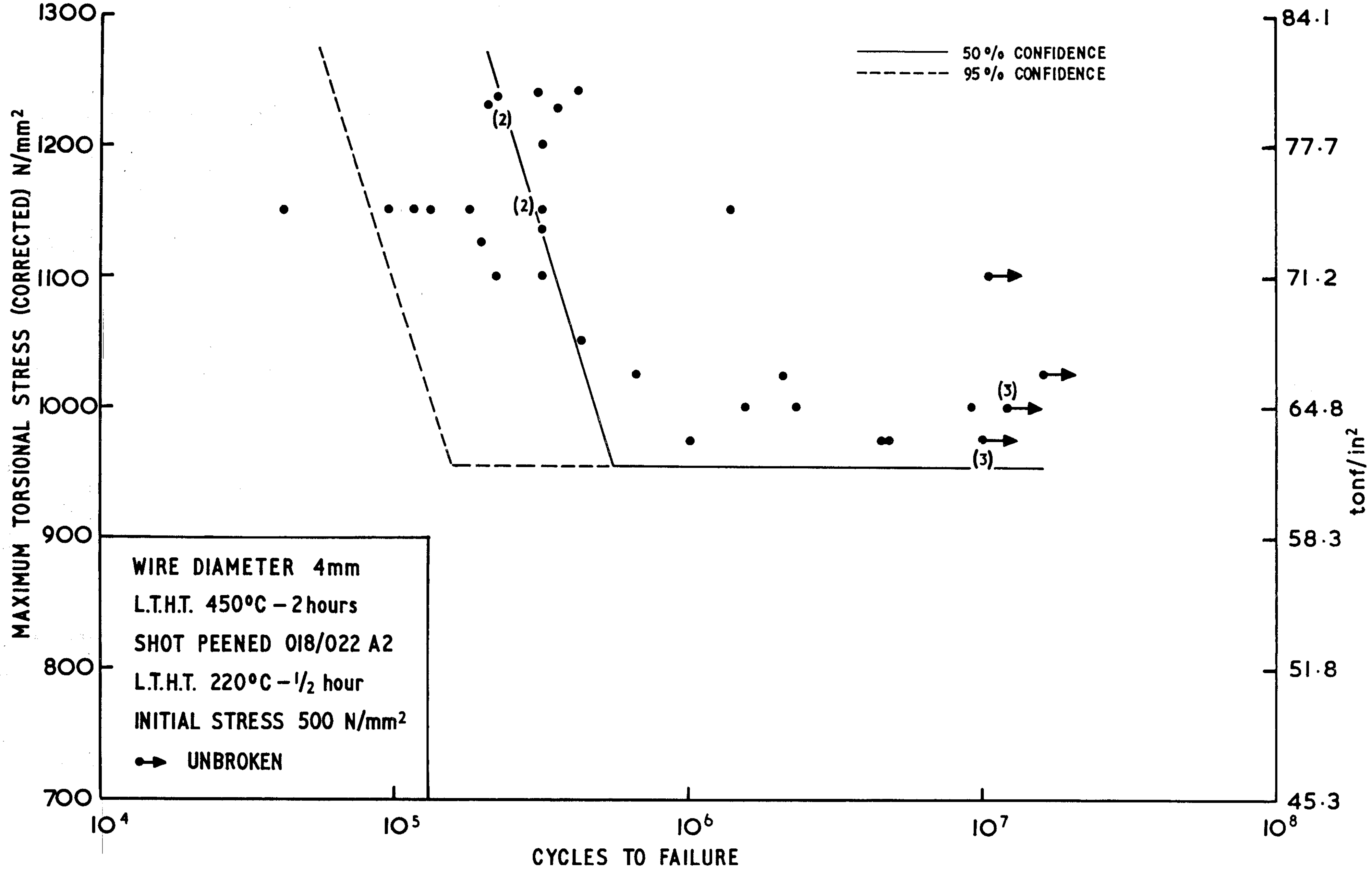


FIG.6 S/N CURVE FOR S205 SHOT PEENED SPRINGS SUPPLIER A

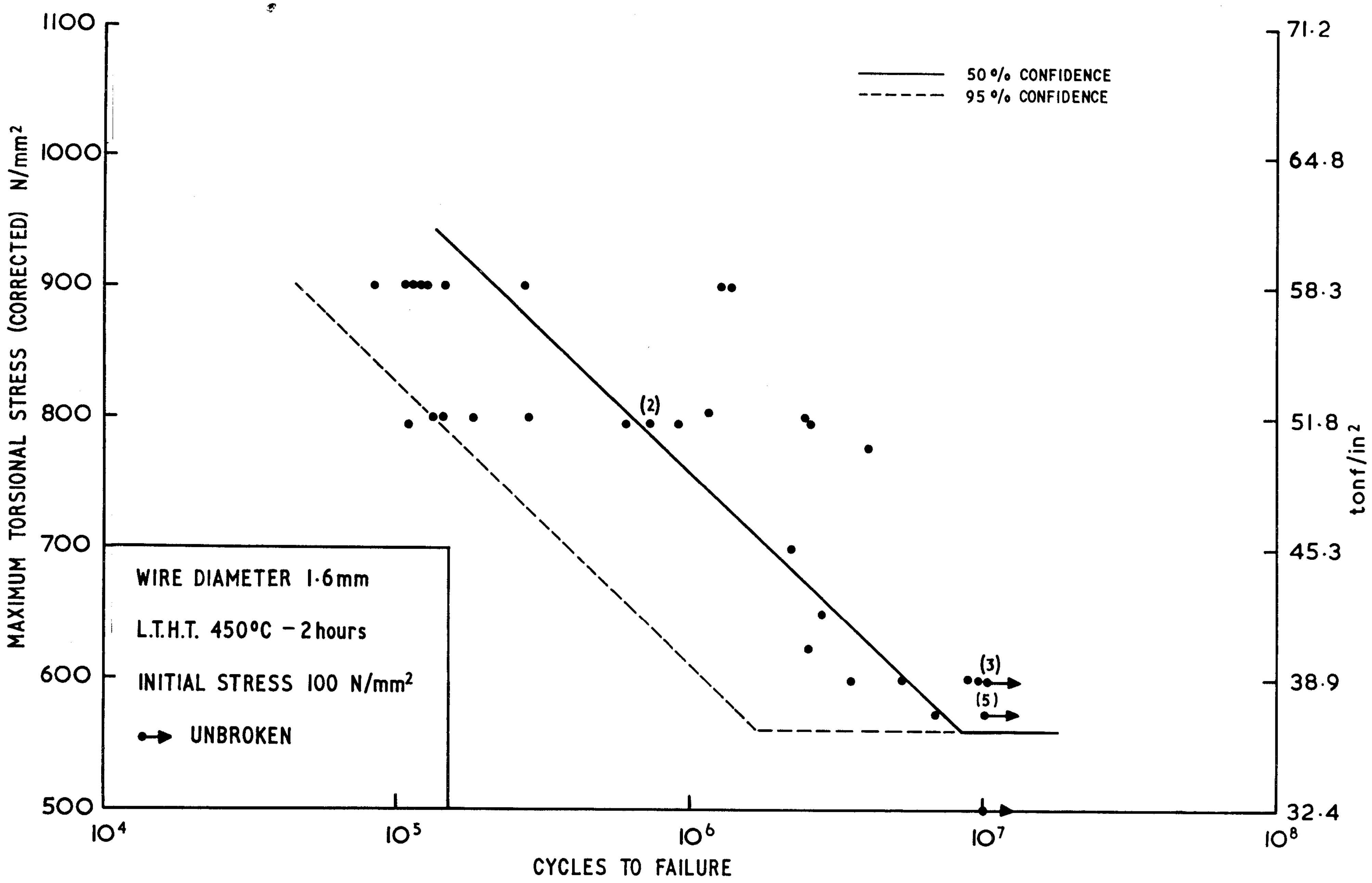


FIG.7 S/N CURVE FOR S205 UNPEENED SPRINGS SUPPLIER A

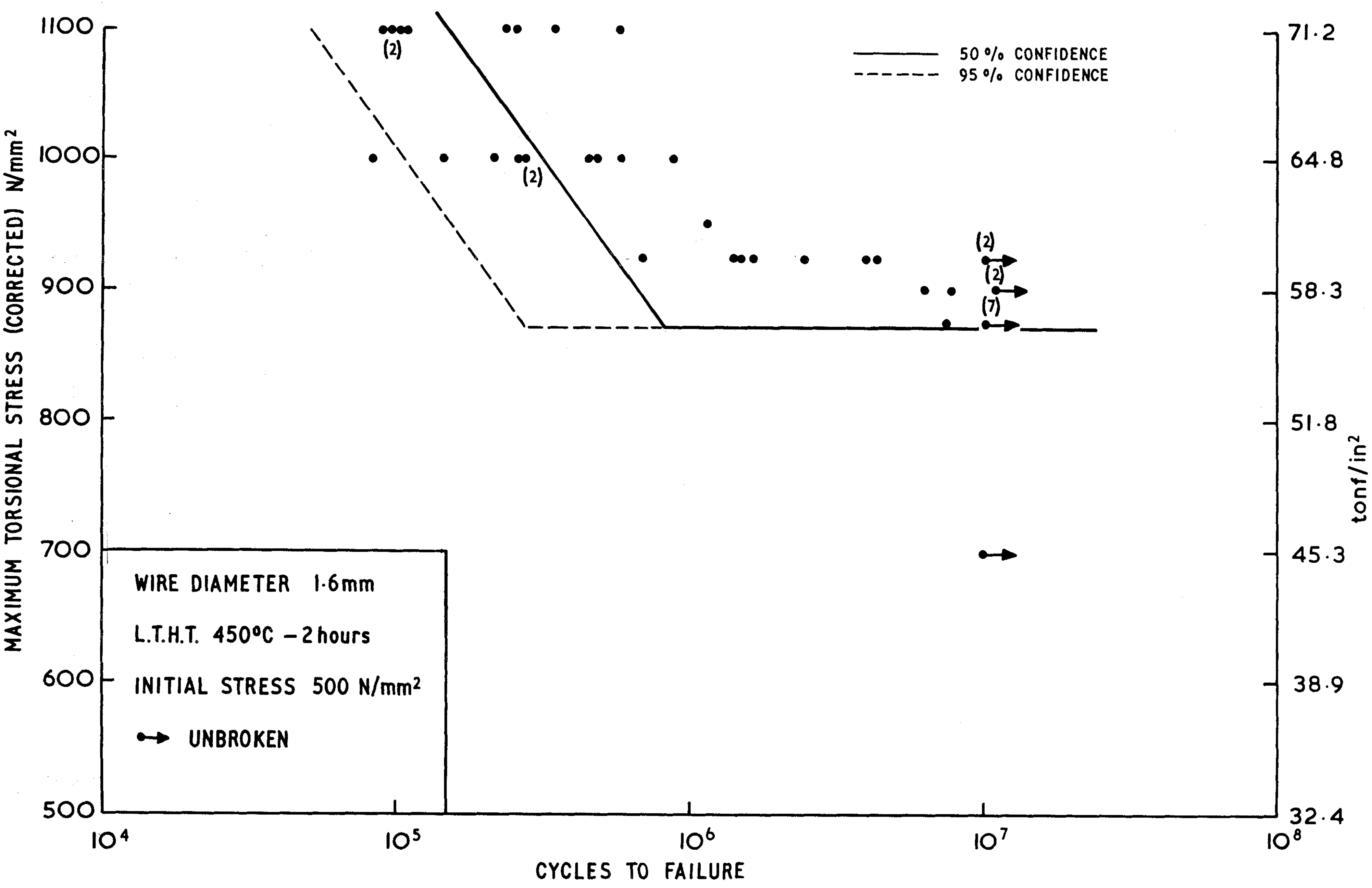


FIG.8 S/N CURVE FOR S205 UNPEENED SPRINGS SUPPLIER A

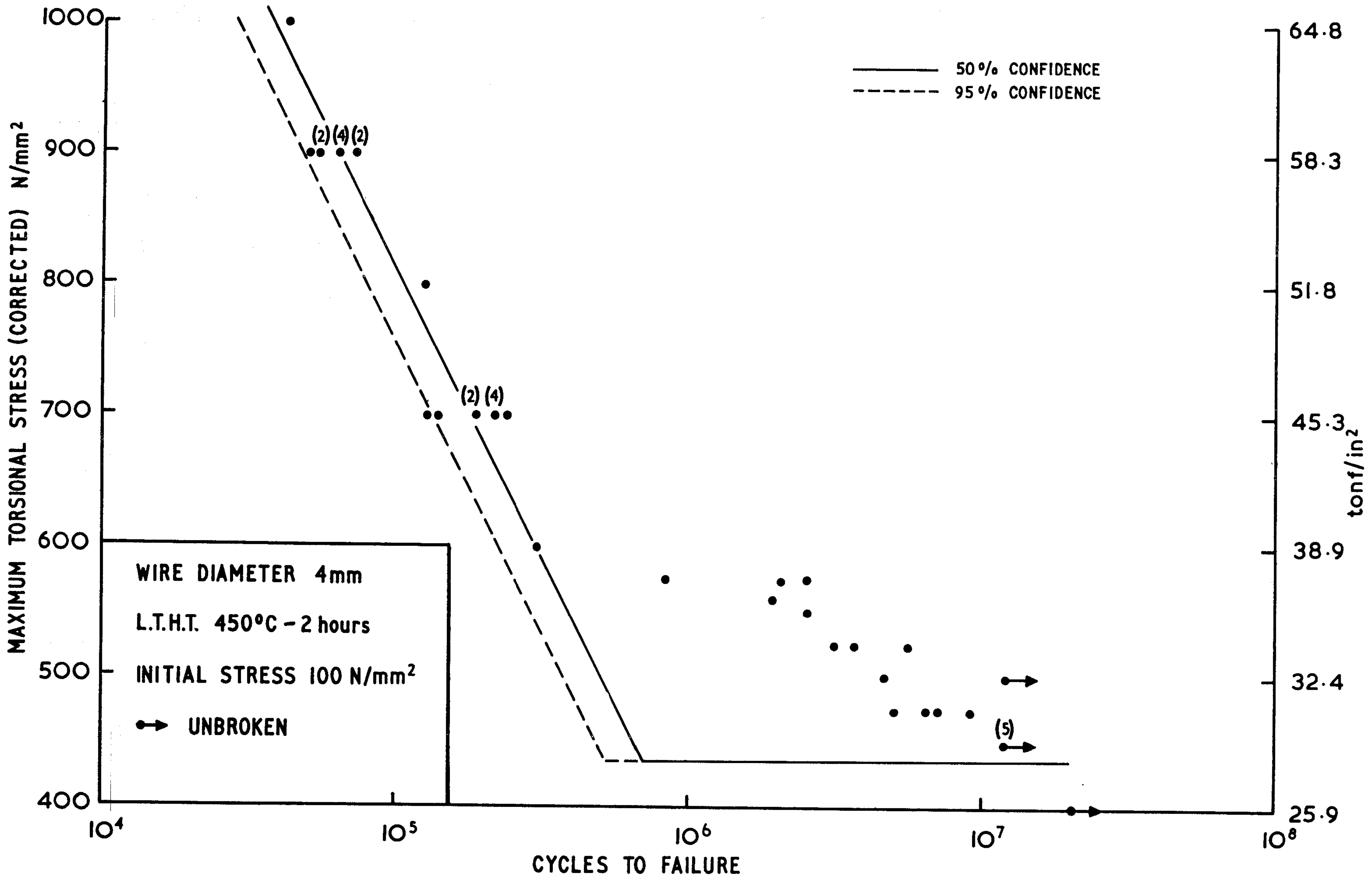


FIG.9 S/N CURVE FOR S205 UNPEENED SPRINGS SUPPLIER B

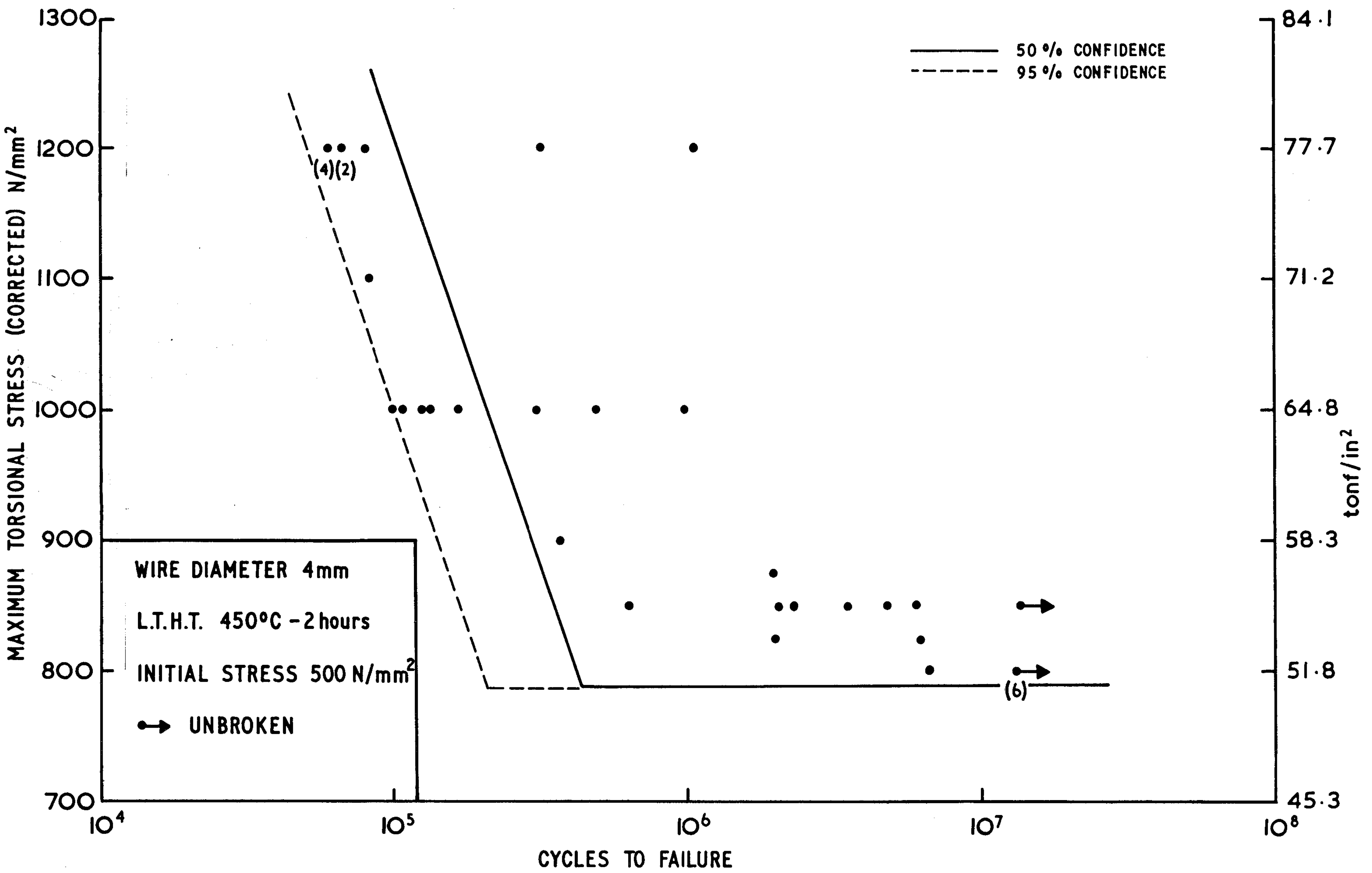


FIG.10 S/N CURVE FOR S205 UNPEENED SPRINGS SUPPLIER B

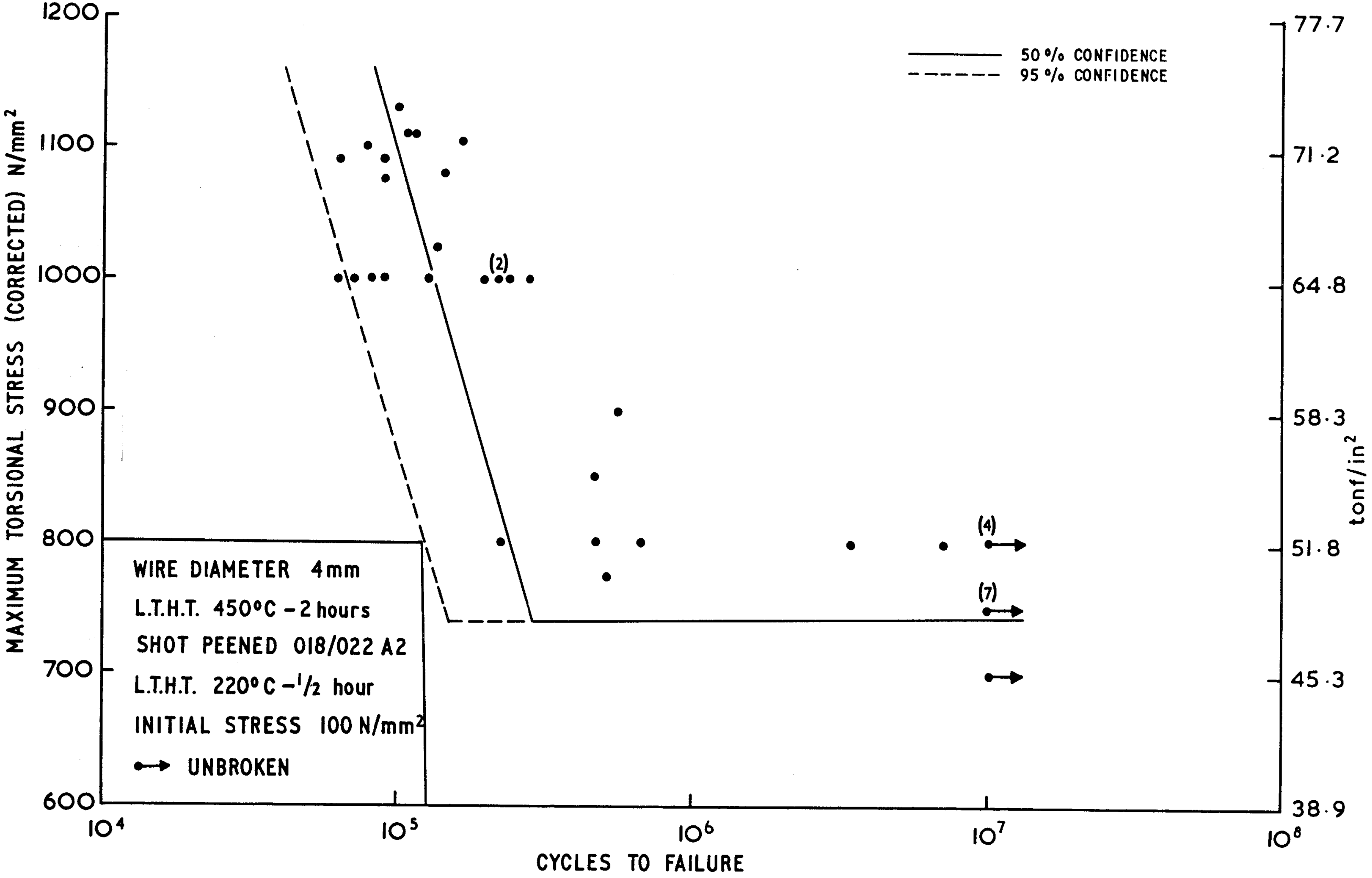


FIG.11 S/N CURVE FOR S205 SHOT PEENED SPRINGS SUPPLIER B

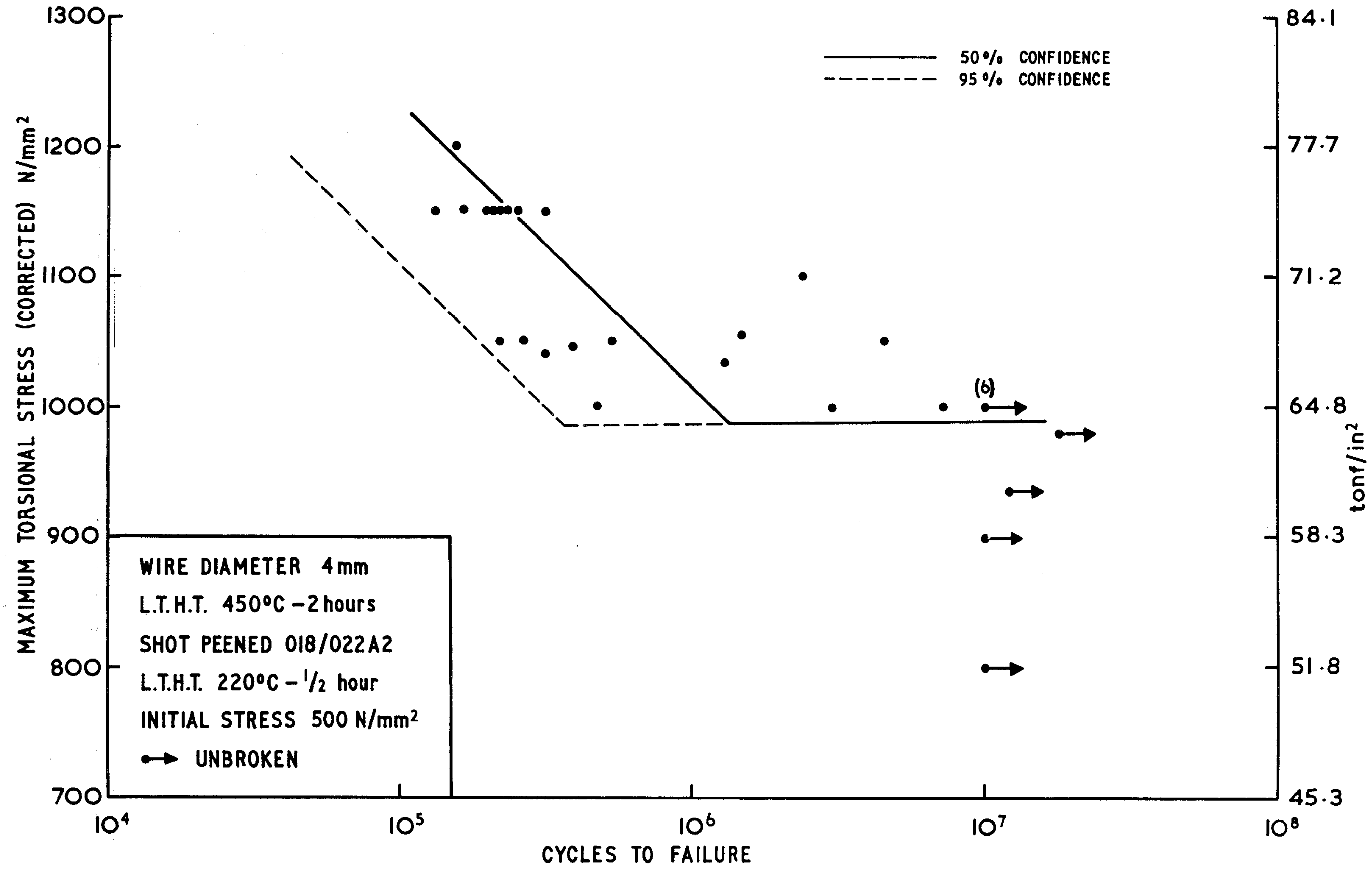


FIG. 12 S/N CURVE FOR S205 SHOT PEENED SPRINGS SUPPLIER B

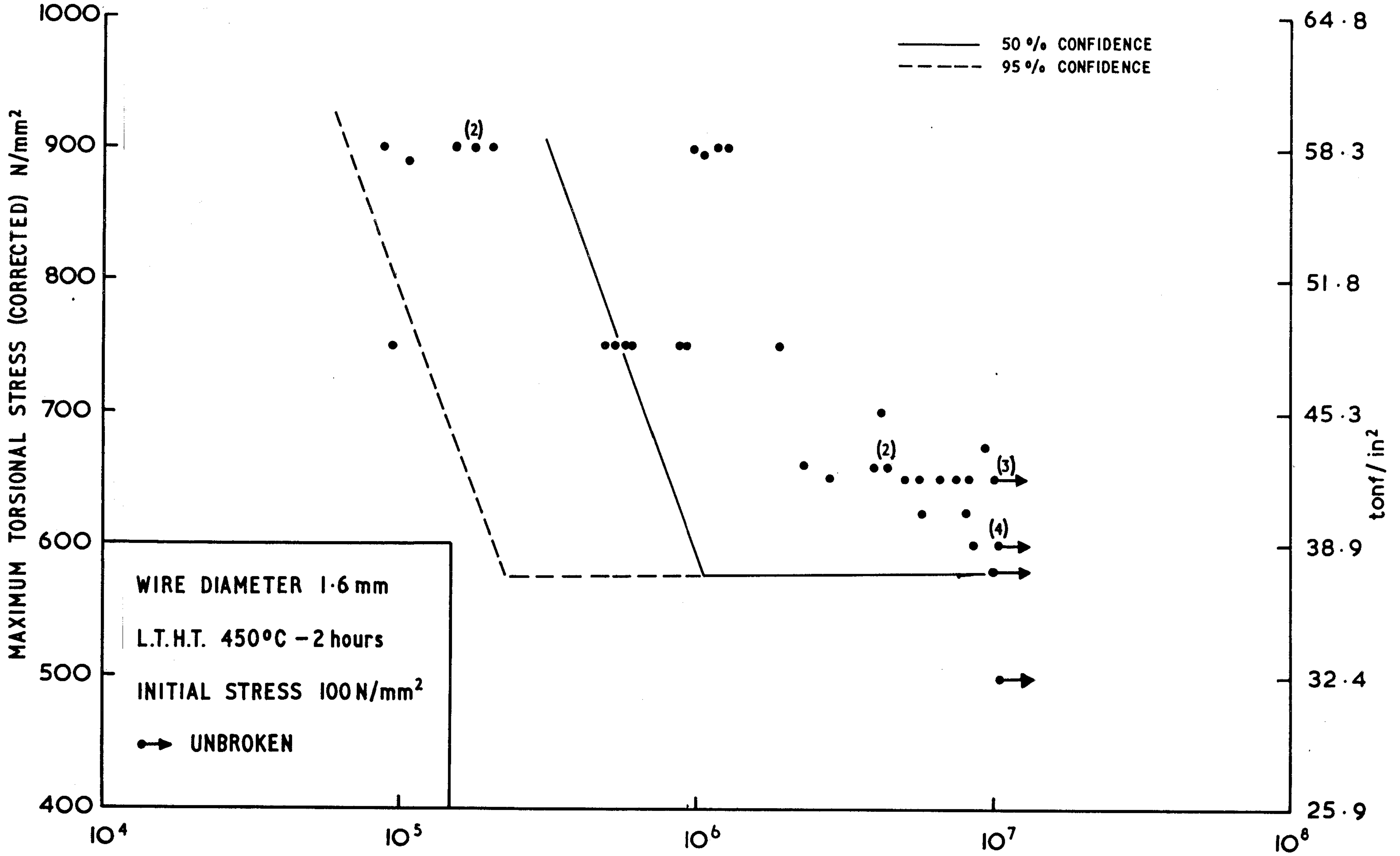


FIG. 13 S/N CURVE FOR S205 UNPEENED SPRINGS SUPPLIER B

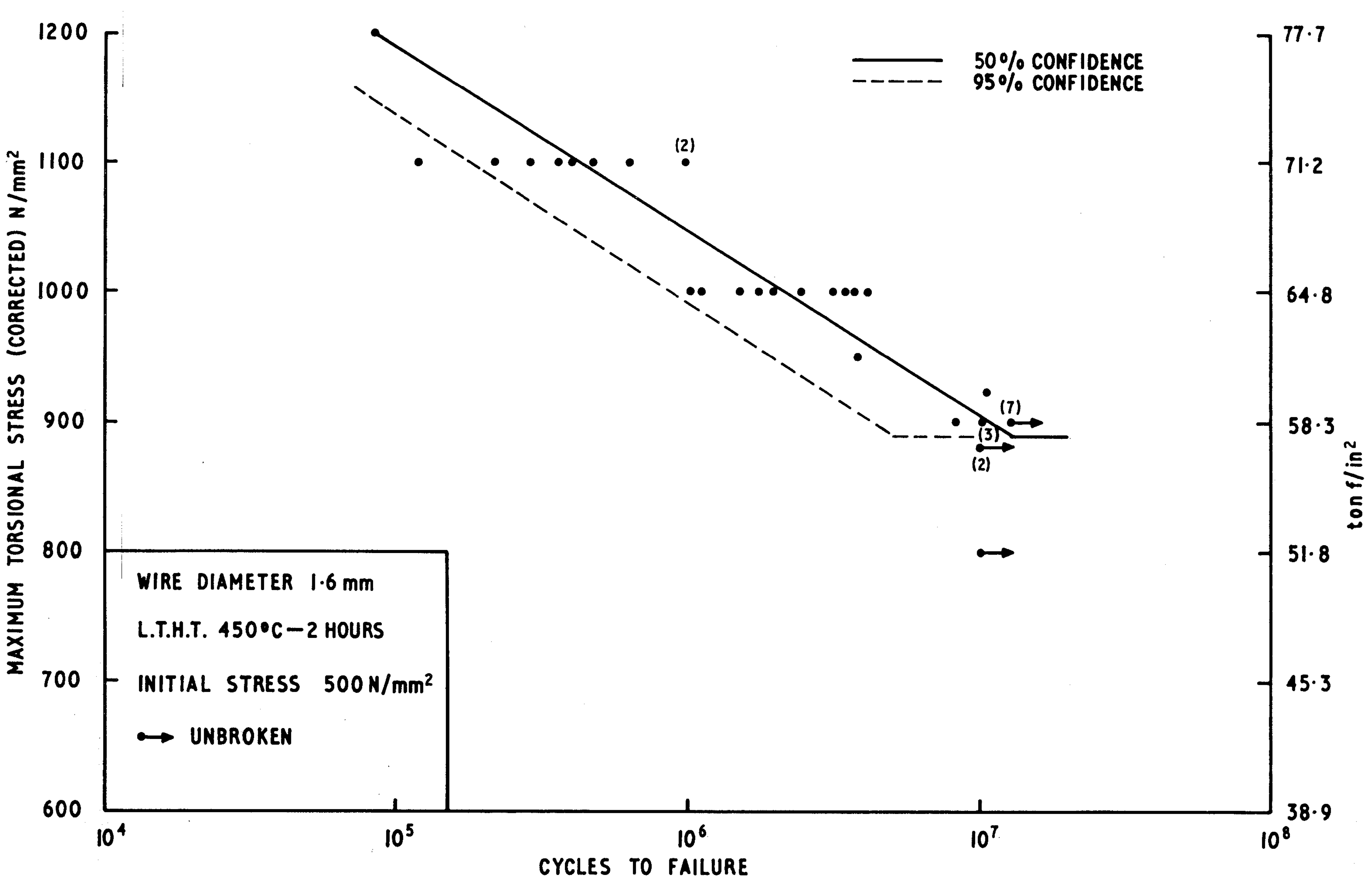


FIG. 14. S/N CURVE FOR S205 UNPEENED SPRINGS SUPPLIER B

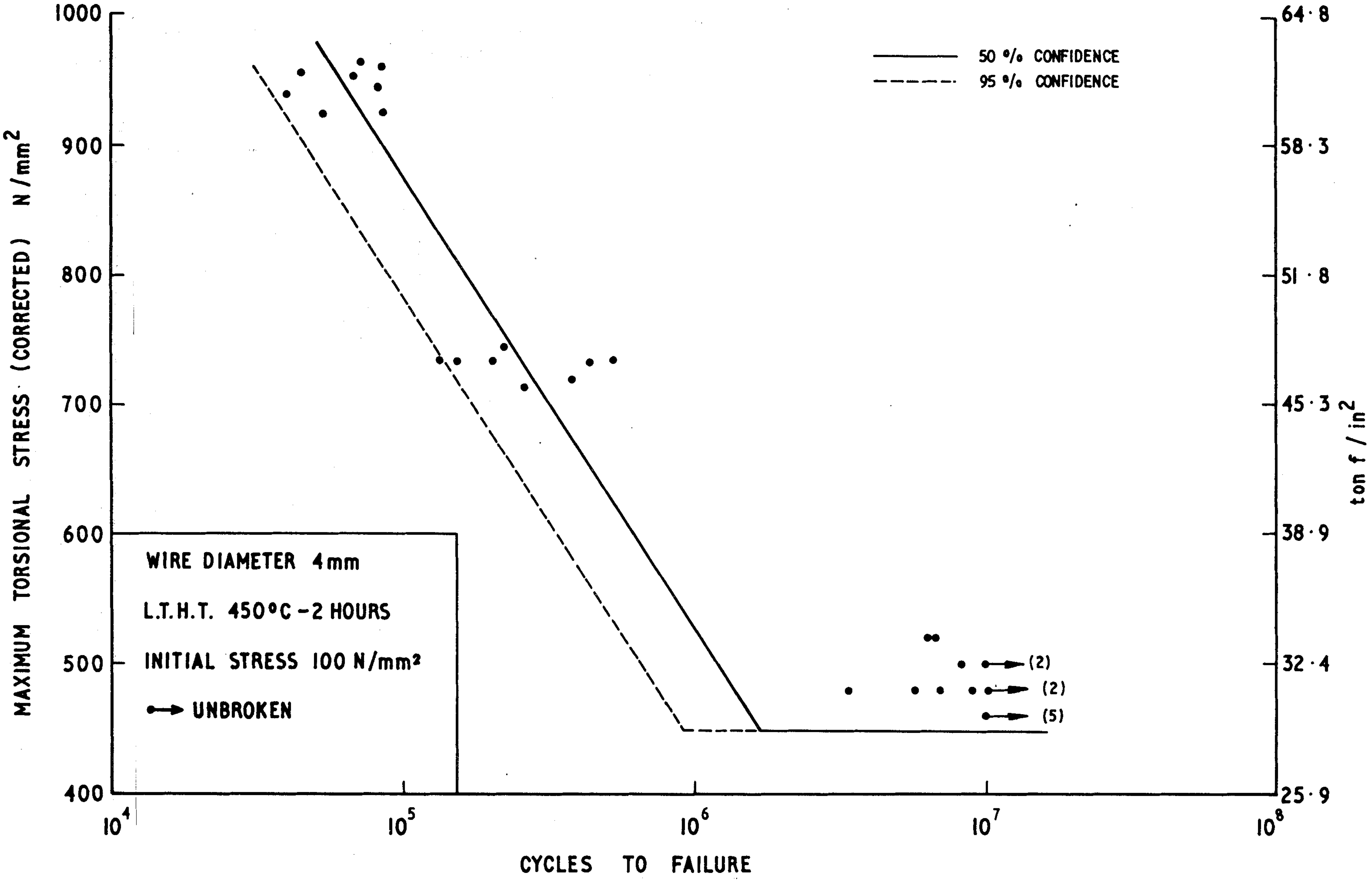


FIG.15 S/N CURVE FOR S205 UNPEENED SPRINGS. SUPPLIER C

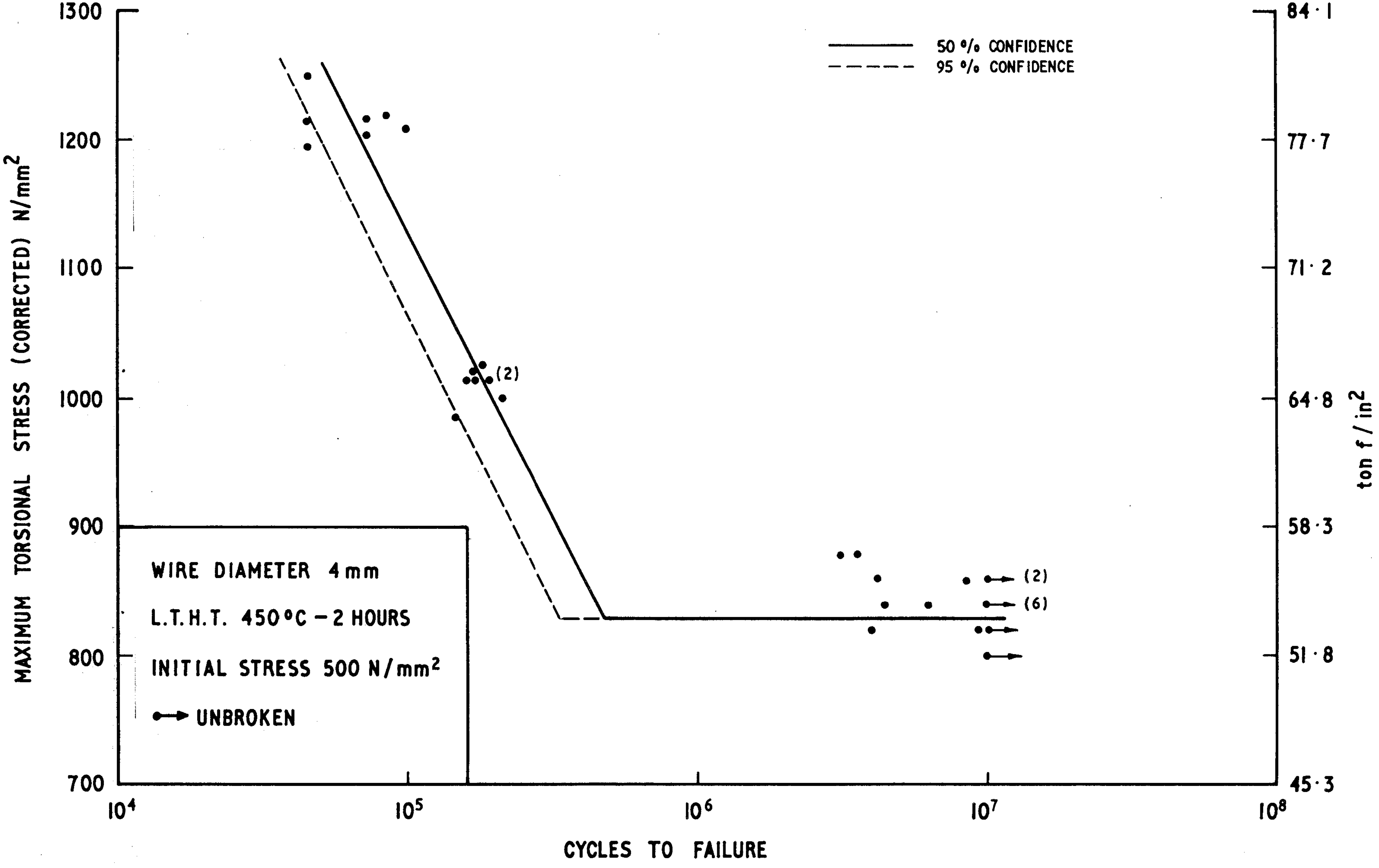


FIG.16 S/N CURVE FOR S205 UNPEENED SPRINGS SUPPLIER C

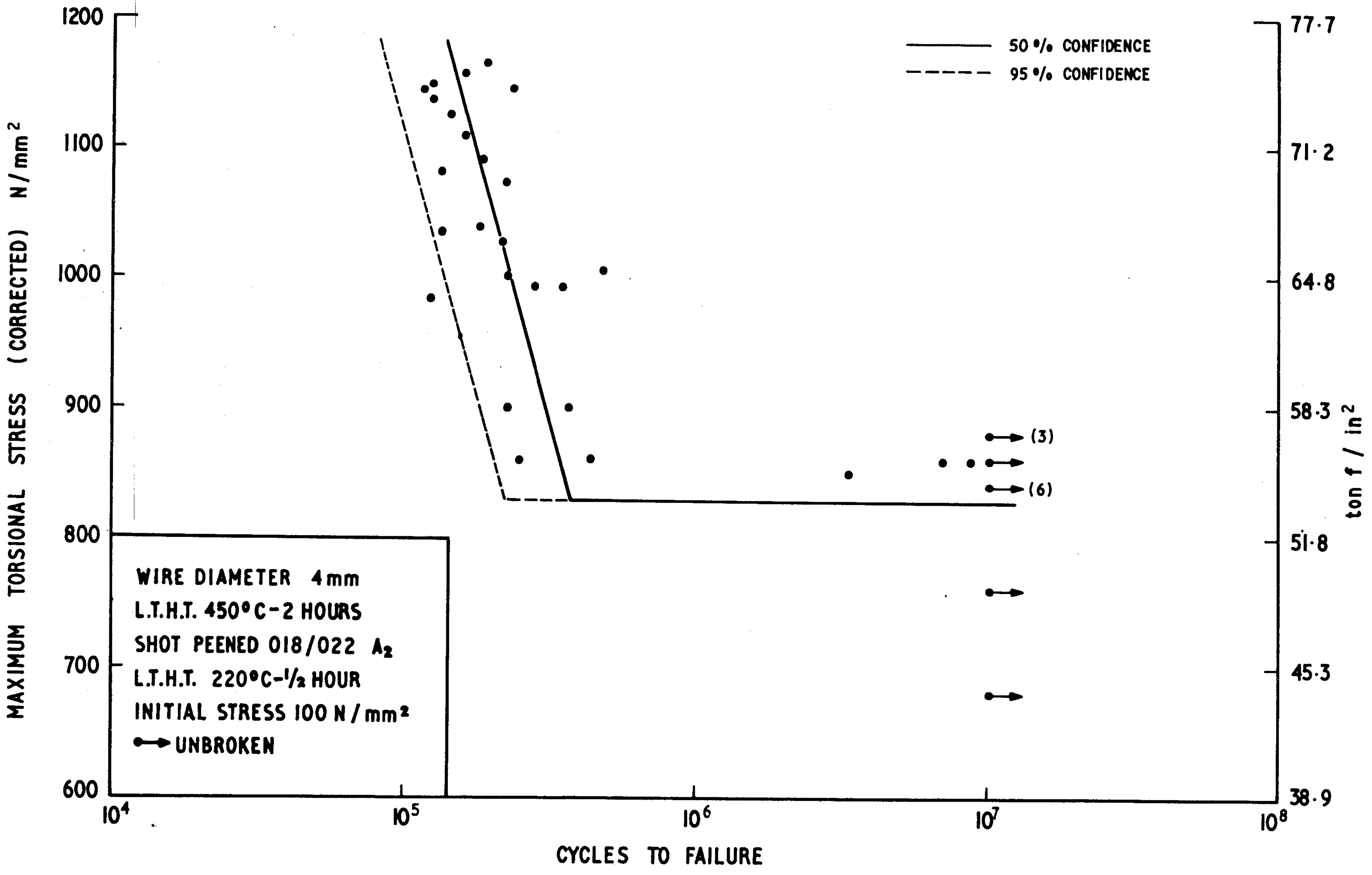


FIG.17 S/N CURVE FOR S 205 SHOT PEENED SPRINGS, SUPPLIER C

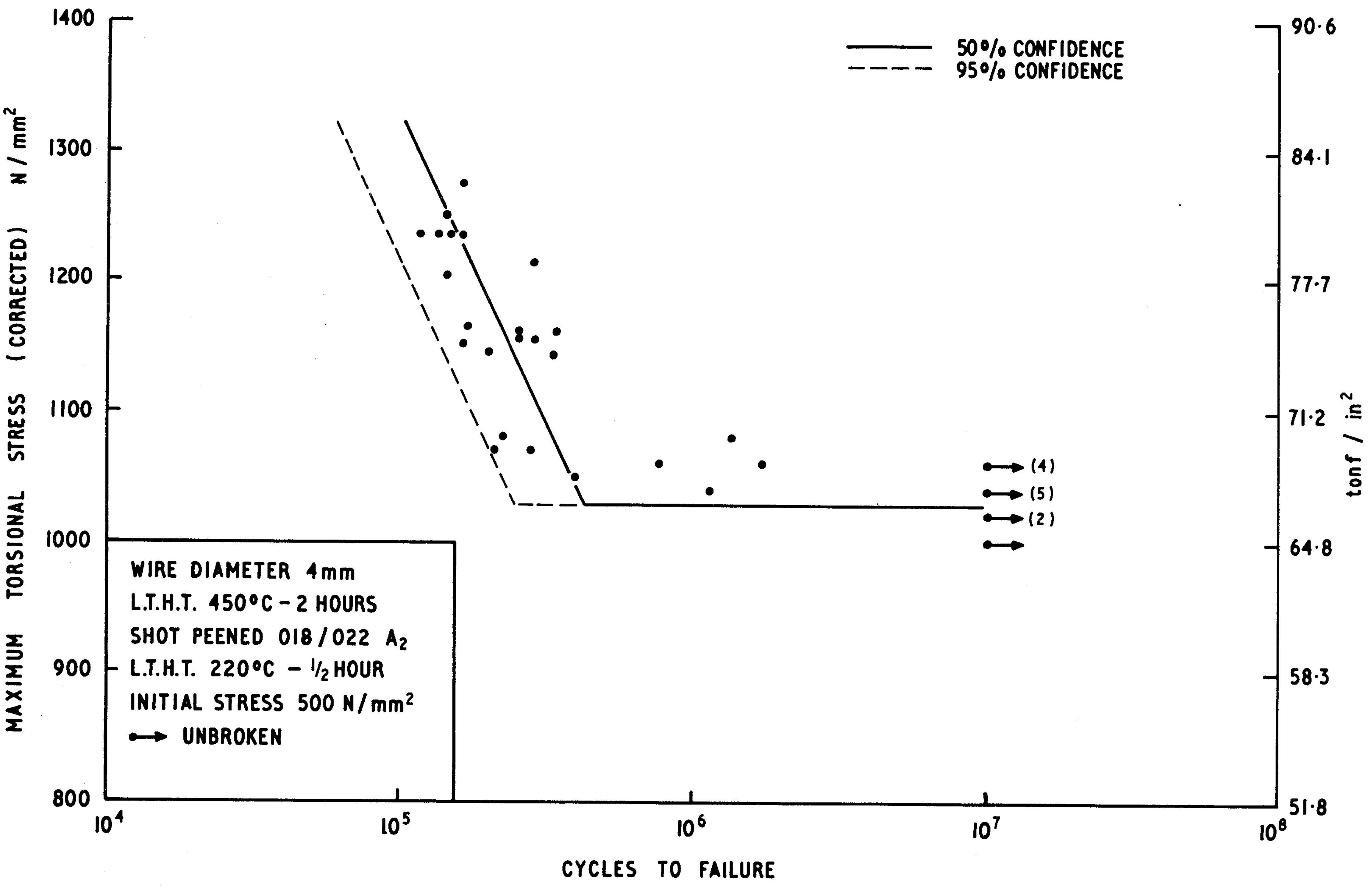


FIG. 18. S/N CURVE FOR S205 SHOT PEENED SPRINGS SUPPLIER C

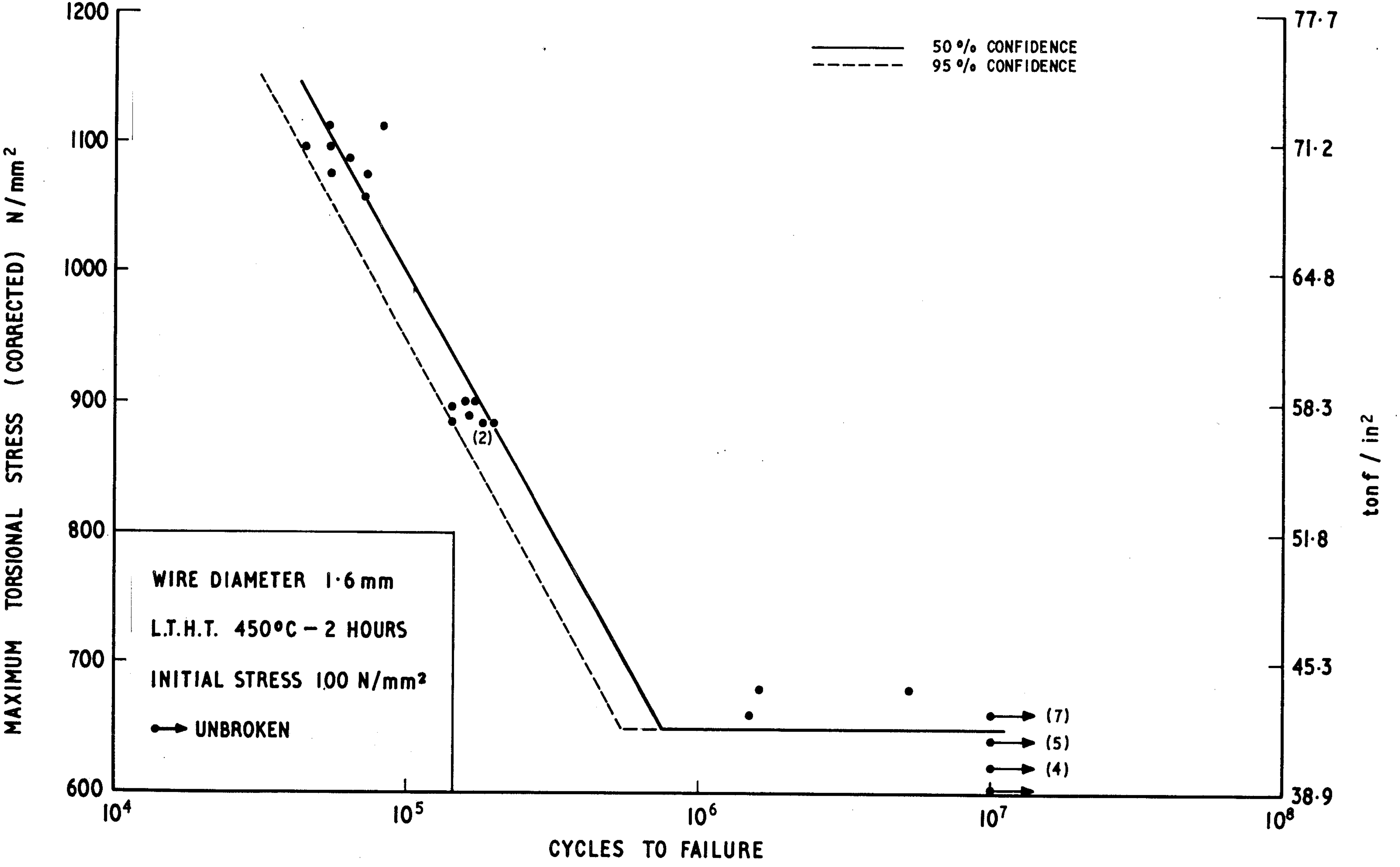


FIG. 19 S/N CURVE FOR S 205 UNPEENED SPRINGS, SUPPLIER C.

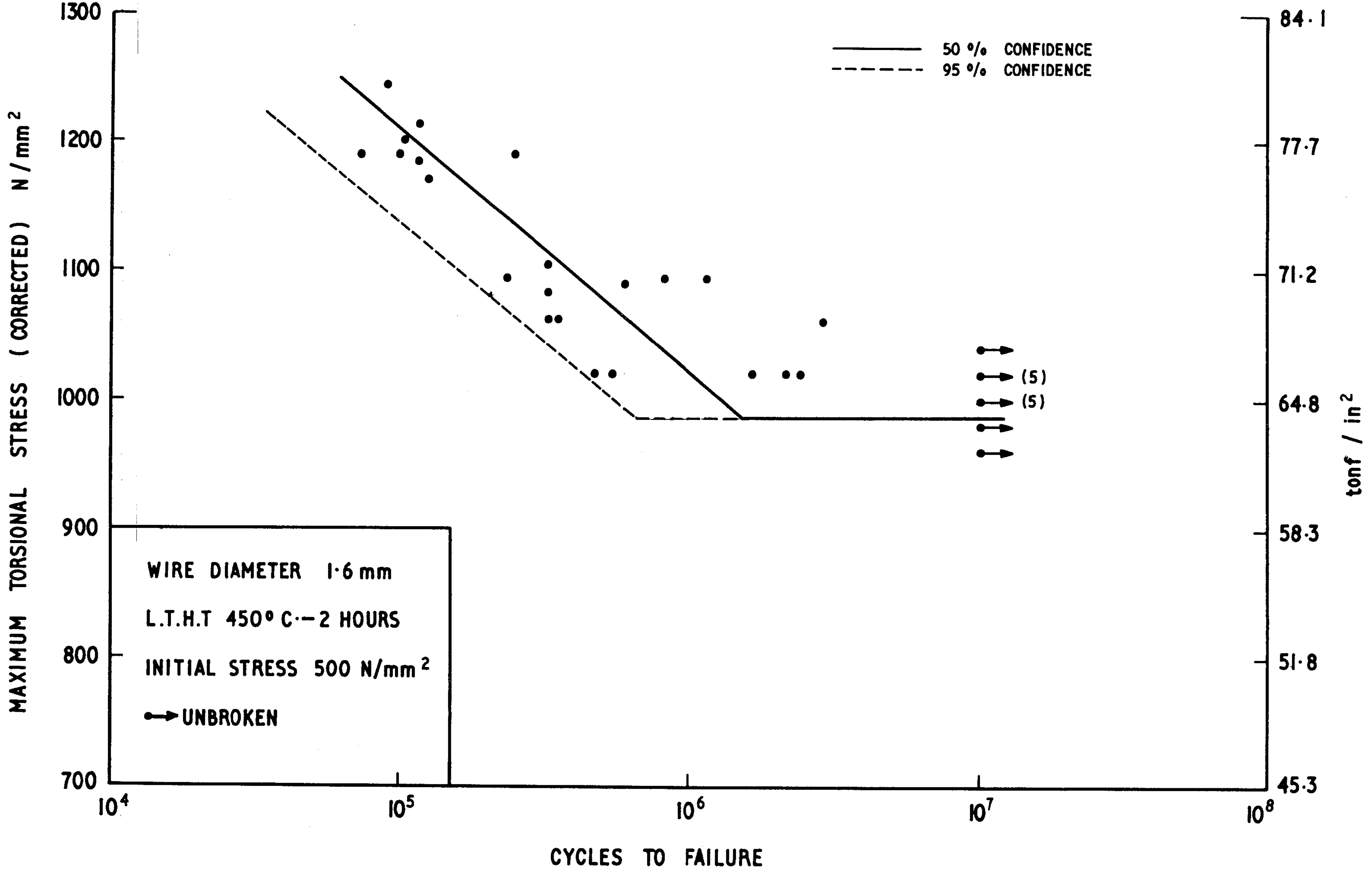


FIG.20 S/N CURVE FOR S 205 UNPEENED SPRINGS, SUPPLIER C.

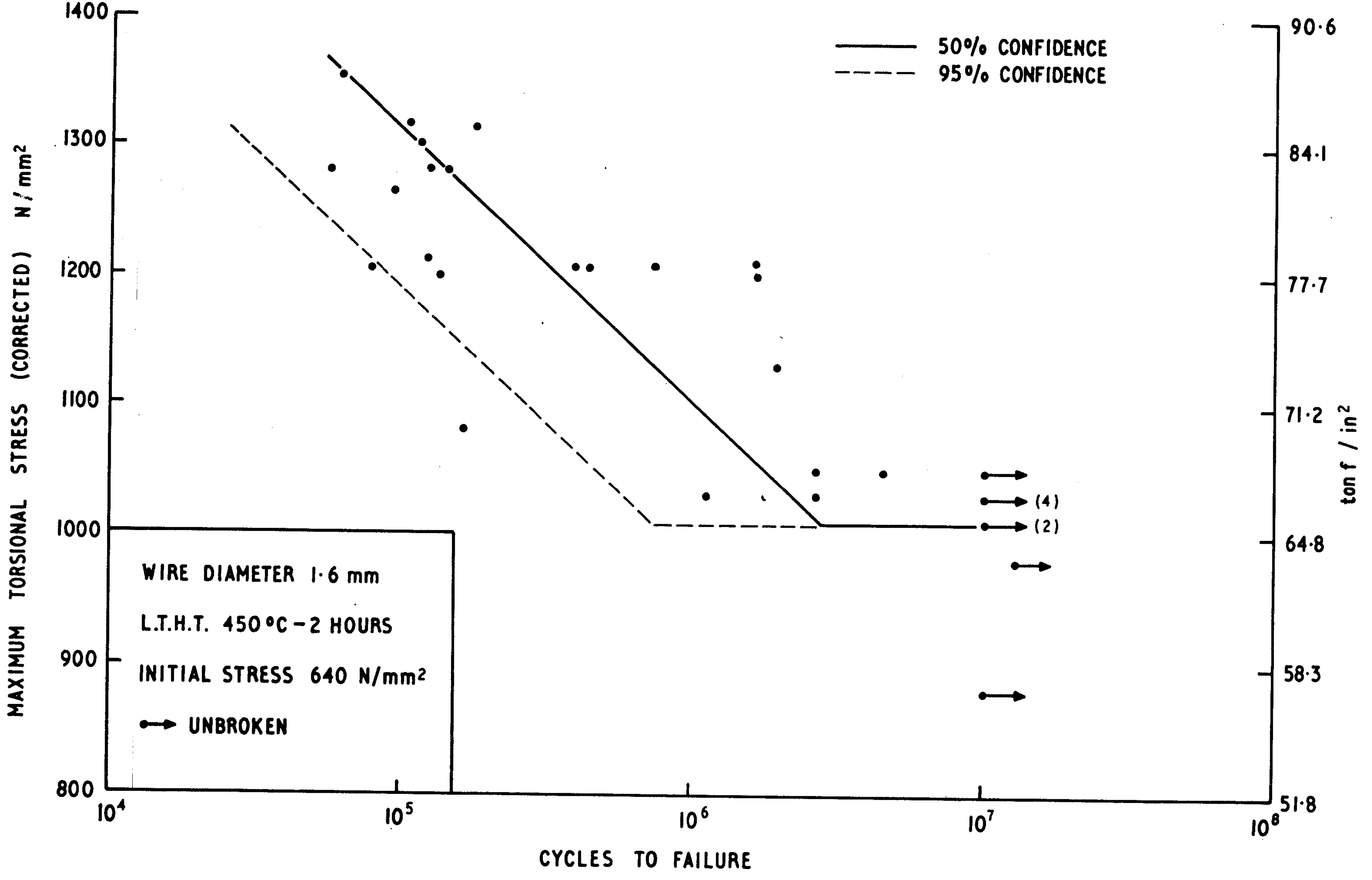


FIG. 21. S/N CURVE FOR S 205 UNPEENED SPRINGS SUPPLIER B

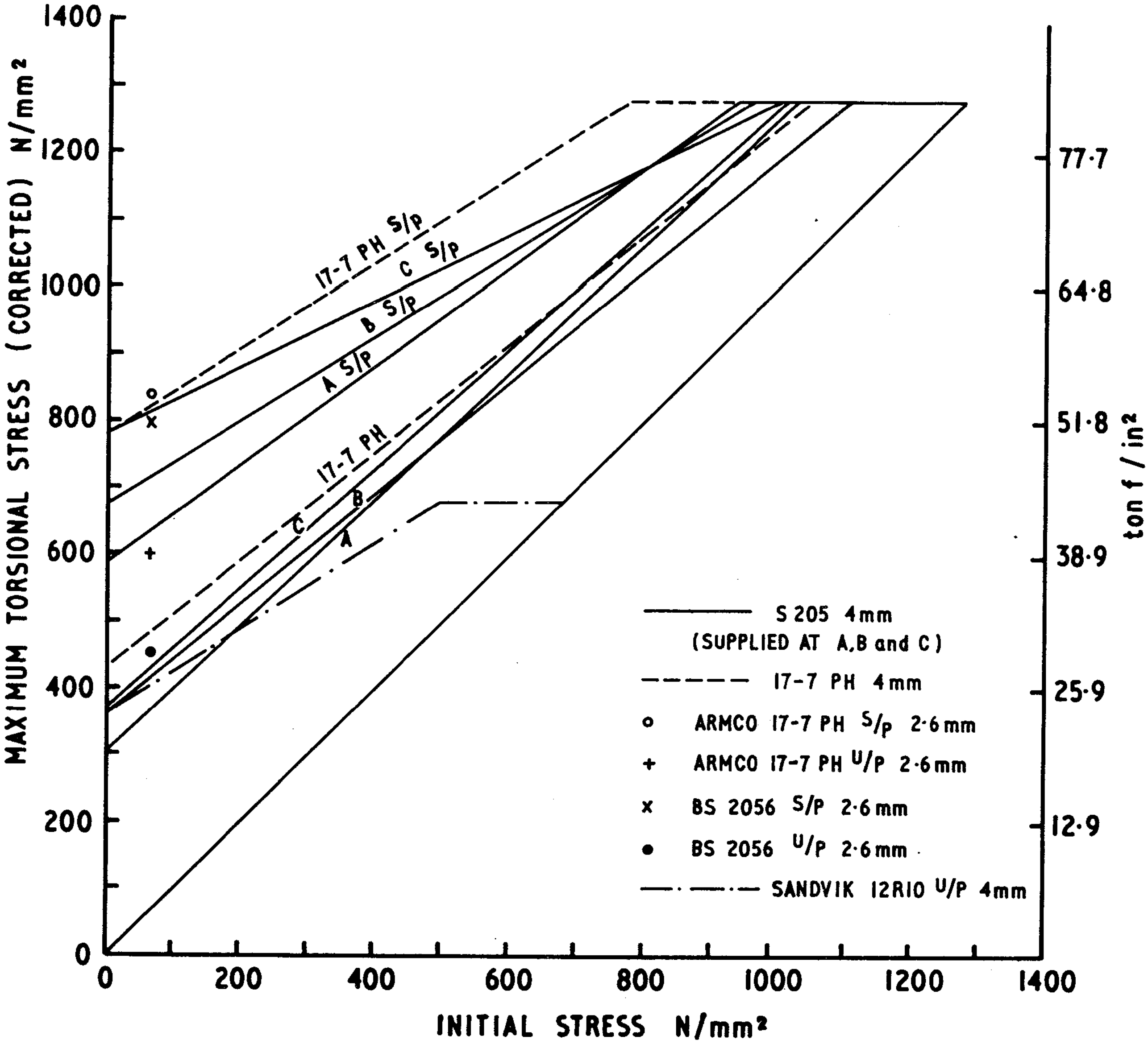


FIG. 22. MODIFIED GOODMAN DIAGRAMS FOR 10^7 CYCLES

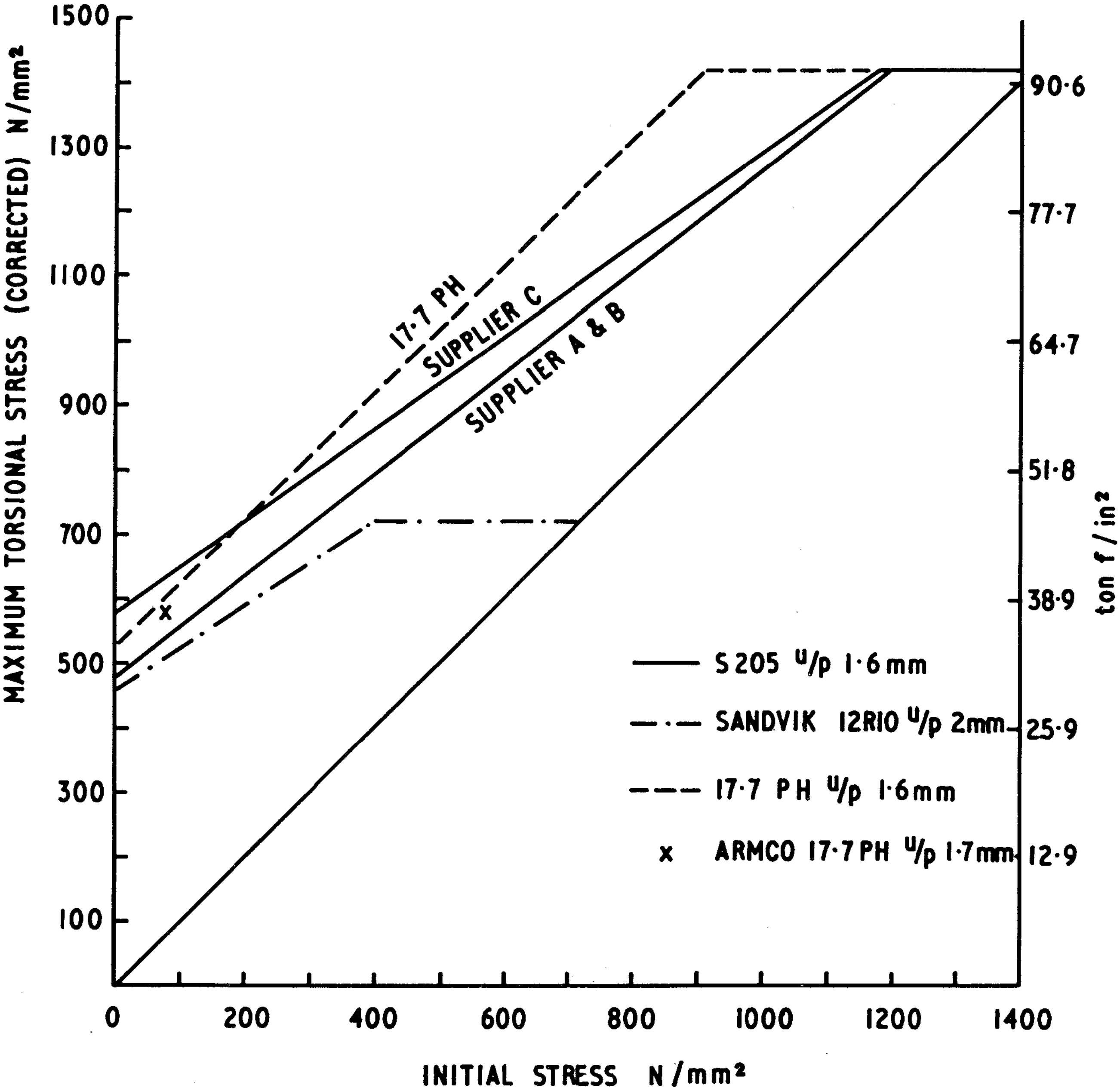


FIG. 23. MODIFIED GOODMAN DIAGRAMS FOR 10^7 CYCLES

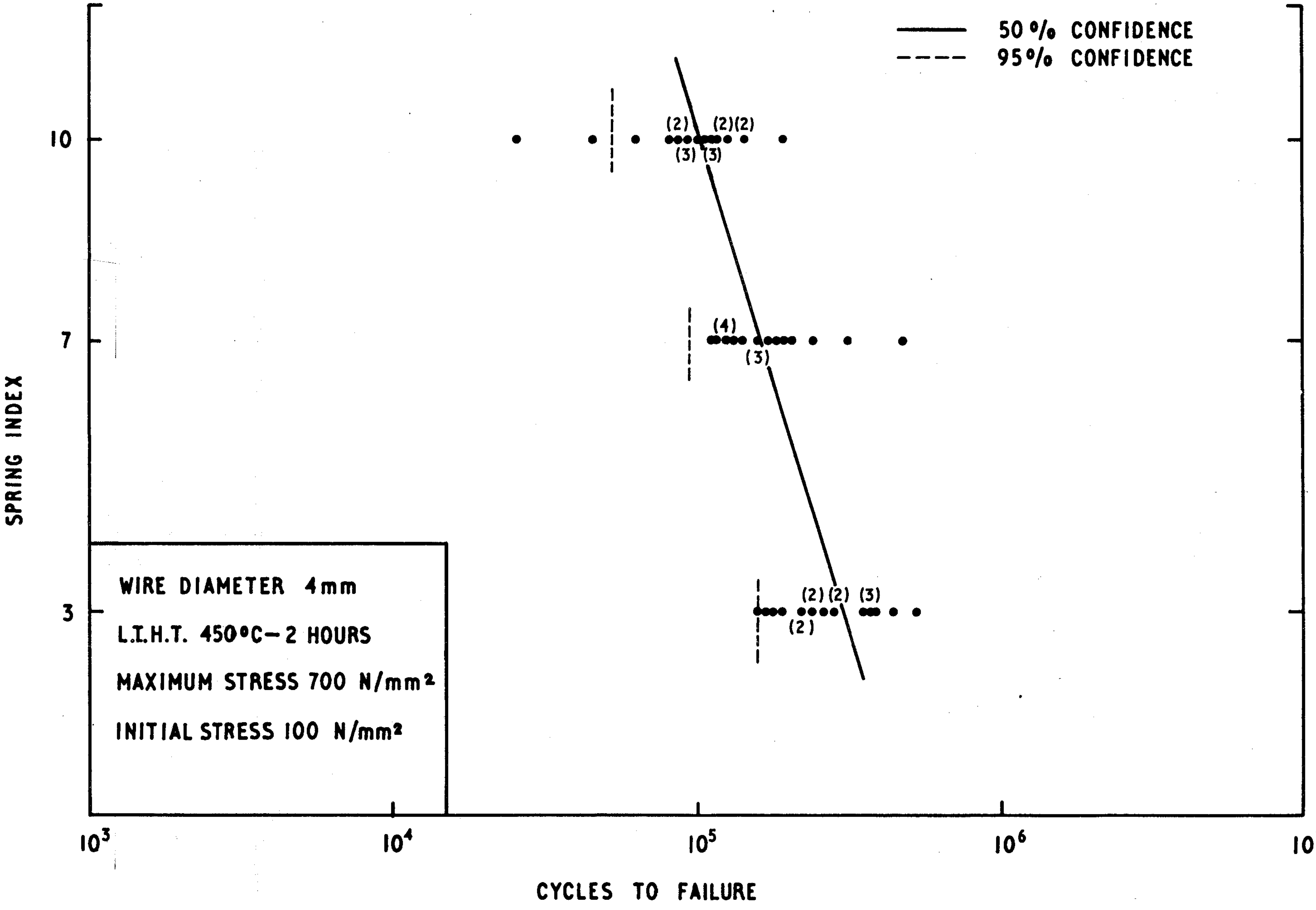
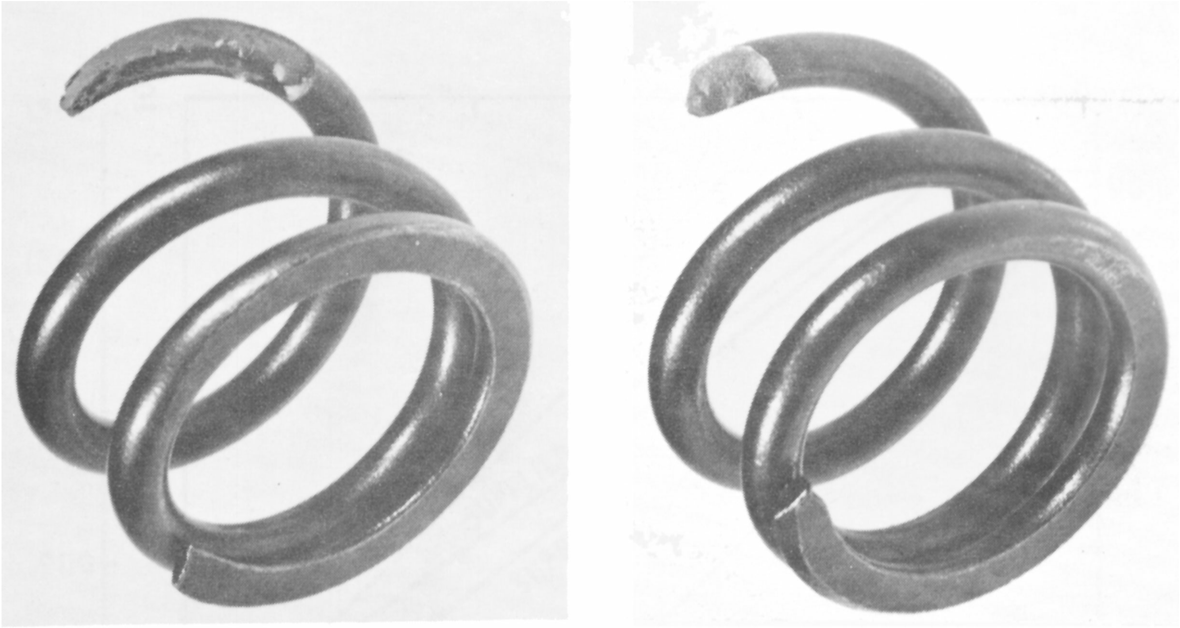
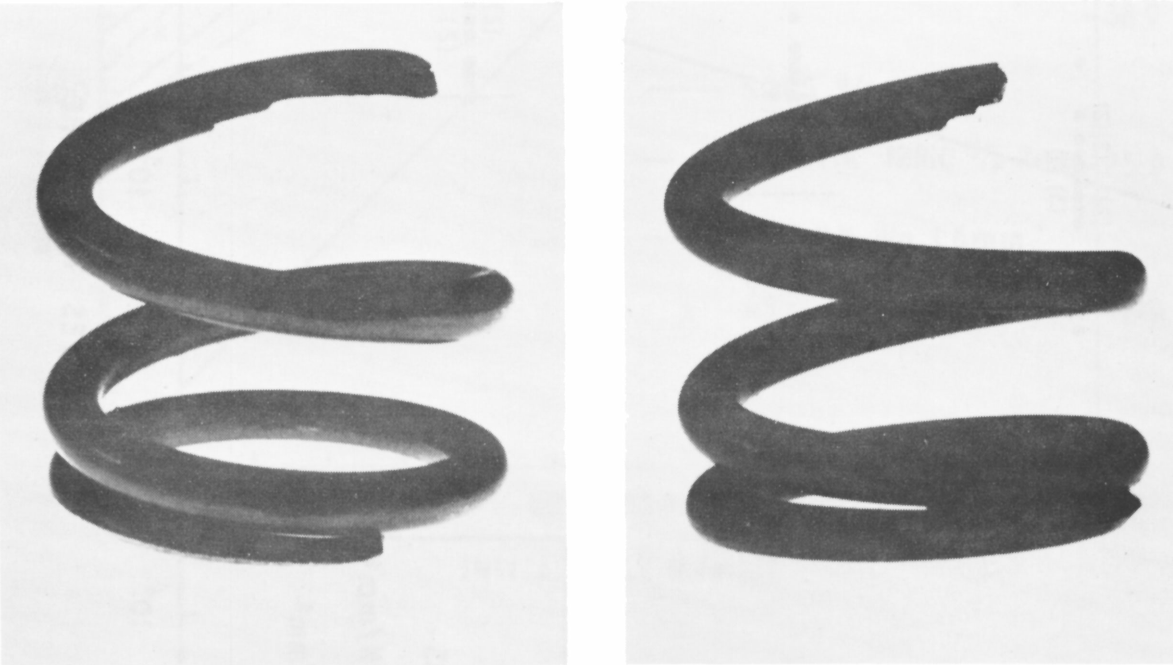


FIG. 24. THE INFLUENCE OF SPRING INDEX ON THE FATIGUE LIFE OF S205 UNPEENED SPRINGS



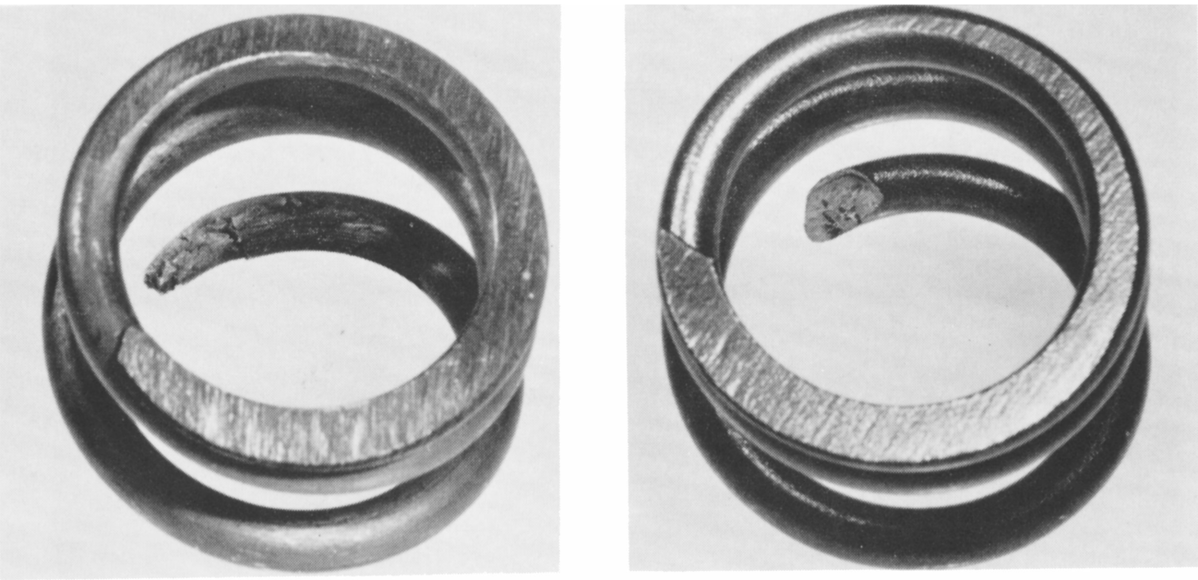
a LOW FATIGUE LIFE b. HIGH FATIGUE LIFE



c. LOW FATIGUE LIFE d. HIGH FATIGUE LIFE

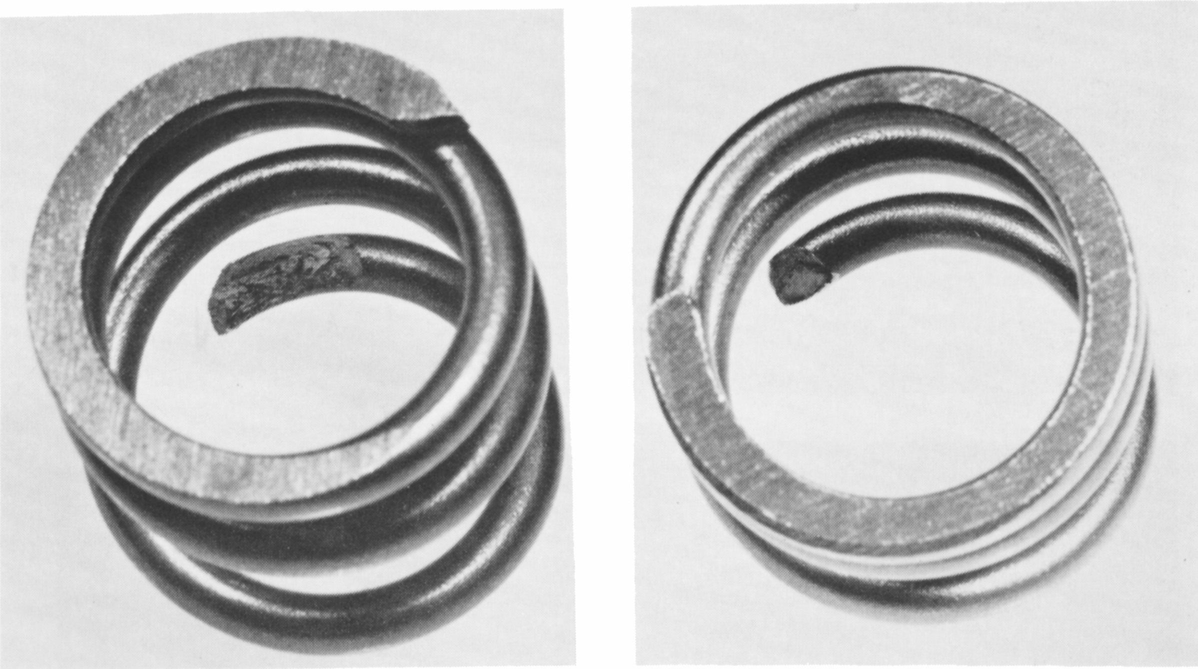
FIG.25 TYPICAL FATIGUE FRACTURES OF SHOT PEENED SPRINGS MADE FROM S205 4mm DIAMETER WIRE

SUPPLIER A X2



a LOW FATIGUE LIFE (UNPEENED) SUPPLIER A

b. LOW AND HIGH FATIGUE LIFE SUPPLIER B



c. LOW FATIGUE LIFE SUPPLIER C

d. HIGH FATIGUE LIFE SUPPLIER C

FIG. 26 TYPICAL FATIGUE FRACTURES OF S205 SPRINGS MADE FROM 4mm DIAMETER WIRE

X2

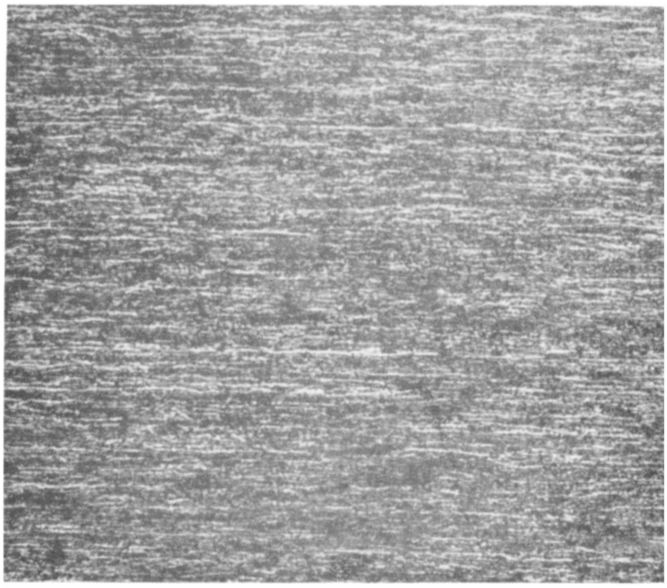


FIG 27a

LONGITUDINAL SECTION OF

s205 4mm DIAMETER WIRE

SUPPLIER A

ETCHANT MARBLES REAGENT

X260

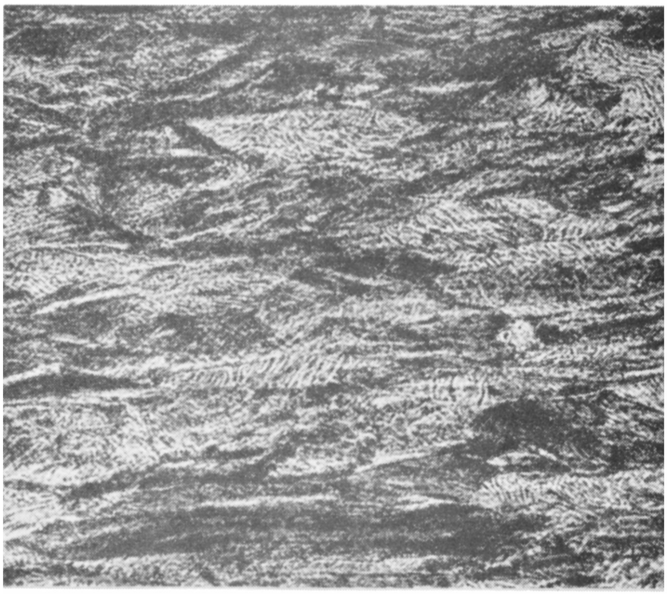


FIG. 27b

LONGITUDINAL SECTION OF

S205 4mm DIAMETER WIRE

SUPPLER B

ETCHANT MARBLES REAGENT

X260

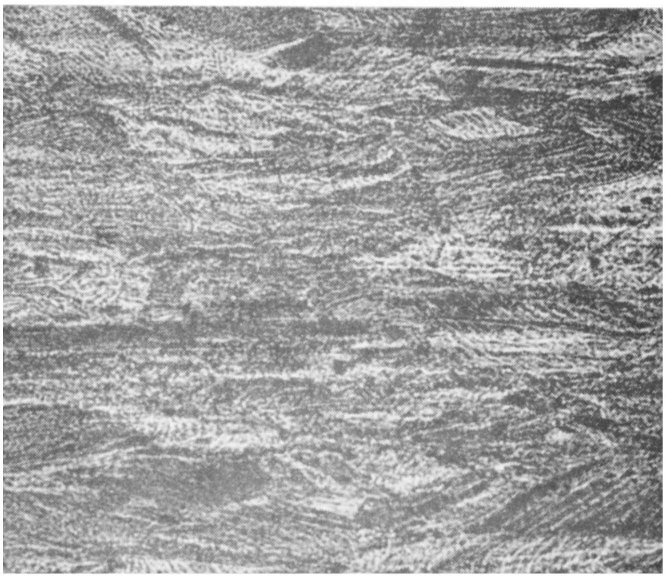


FIG. 27c

LONGITUDINAL SECTION OF

S205 4mm DIAMETER WIRE

SUPPLIER C

ETCHANT MARBLES REAGENT

X260

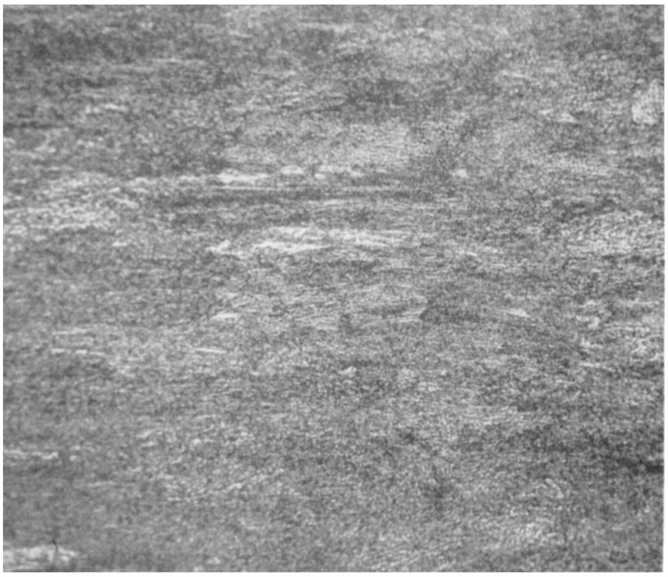


FIG. 28a

LONGITUDINAL SECTION OF S205 1.6mm DIAMETER WIRE

SUPPLIER A

ETCHANT MARBLES REAGENT

X250

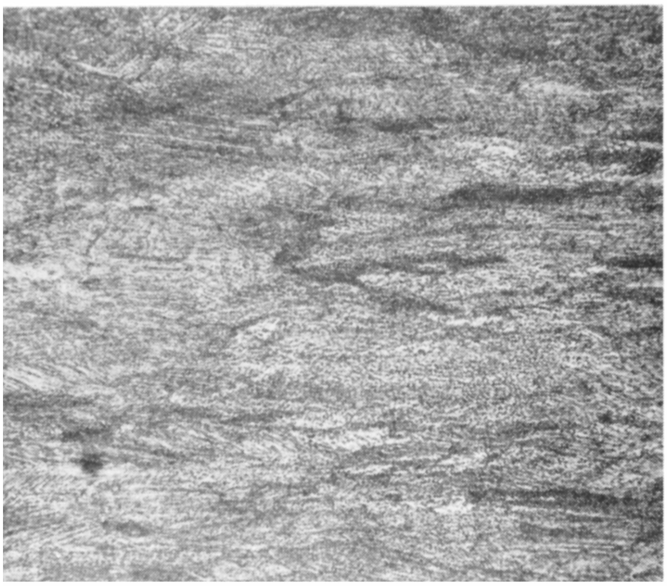


FIG. 28b

LONGITUDINAL SECTION OF S205 1.6mm DIAMETER WIRE

SUPPLER B

ETCHANT MARBLES REAGENT

X250

FIG. 28c

LONGITUDINAL SECTION OF S205 1.6mm DIAMETER WIRE

SUPPLIER C

ETCHANT MARBLES REAGENT

X250