THE SPRING RESEARCH ASSOCIATION

THE FATIGUE PROPERTIES OF HELICAL COMPRESSION SPRINGS MANUFACTURED FROM 17-7 PH WIRE

(Contract No. K43A/65/CB43A2)
Progress Report No. 3

by

S. D. Gray, A.P. (Sheff.)
Report: 198

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SUMMARY

Fatigue tests have been carried out on springs manufactured from 4 mm (0.160 in) and 1.6 mm (0.064 in) diameter 17-7 PH quality spring wire. Additional tests have also been carried out to assess the response to shot peening of springs made from the 4 mm diameter wire.

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

Unpeened springs made from 4 mm diameter 17-7 PH spring wire had a similar fatigue strength, at a low initial stress level, to those made from B.S. 2056 quality material.

Shot peened springs manufactured from 4 mm diameter wire also had a similar fatigue strength, when tested at low initial stress levels, to peened springs manufactured from B.S. 2056 and Armco 17-7 PH spring material. Shot peening of springs made from 4 mm wire produced a 68% increase in fatigue strength.

Unpeened springs manufactured from 1.6 mm wire had an equivalent fatigue strength to unpeened springs manufactured from Armco 17-7 PH spring steel wire.

(January 1972)

CONTENTS

Page No.

CONTENTS cont... Page No.

9. Tables

10. Figures

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1. INTRODUCTION

17-7 PH material is a semi-austenitic 17% chromium 7% nickel precipitation-hardening stainless steel. Stainless steels of this type are known for their good corrosion resistance, minimum distortion on heat treatment and excellent elastic properties. Because of these inherent characteristics, together with its good cold workability, 17-7 PH stainless steel should prove an ideal spring material.

A programme of research was drawn up by The Spring Research Association and financial support provided by the Ministry of Defence (Aviation) to assess the potential of 17-7 PH material, along with other conventional aircraft spring materials, under fatigue conditions. At the time of commencement of the research programme no British Standard was in existence for 17-7 PH wire, although material of this type was occasionally used for special spring applications. It was decided therefore to base the research on wire available to the spring trade at that time. During the course of this work, however, a new British Standard for 17-7 PH wire was published as D.T.D. 5086 and although the wire used for the research meets many of the B.S. requirements not all are satisfied.

Fatigue data have been obtained on helical compression springs manufactured from 17-7 PH spring material. Two wire sizes have been examined, namely 4 mm (0.160 in) and 1.6 mm (0.064 in) diameter. Additional tests have also been carried out to examine the response to shot peening of springs made from the 4 mm diameter wire.

2. MATERIAL

2.1 Wire

17-7 PH wire, from a British source, hard drawn from rod, was supplied in two sizes, i.e. 4 mm and 1.6 mm diameter, both in the unaged condition, to tensile strengths of 1377 N/mm^2 (89.2 tonf/in^2) and 1549 N/mm^2 (100.3 tonf/in^2) for the 4 mm and 1.6 mm wires respectively.

The actual chemical analyses of the wires are given in Table I. For comparison purposes the composition specification for wire to D.T.D. 5086 is given in Table II.

2.2 Springs

The design details of the two types of springs tested are given in Table III. Coiling was carried out in the as-drawn condition followed by a batch precipitation hardening treatment at a recommended temperature of 480°C for one hour, in an attempt to produce the optimum increase in tensile properties.

Following end grinding and prestressing to solid, a batch of springs made from 4 mm diameter wire was shot peened to an Almen Arc rise of 0.018/0.022 A2, followed by a low temperature heat treatment of 220°C for $\frac{1}{2}$ hour.

3. EXPERIMENTAL PROCEDURE

3.1 Fatigue Testing

Springs were individually load tested to establish the necessary fatigue machine strokes to give the required stress ranges. In most cases fatigue testing was carried out at two initial stress levels, i.e. 100 N/mm^2 and 500 N/mm^2, on forced motion multiple spring testing machines. When testing 4 mm unpeened springs at an initial stress of 500 N/mm^2, a large amount of scatter in fatigue strength occurred due to the springs working close to solid, therefore it was impossible to obtain a reliable fatigue limit. By reducing the initial stress to 400 N/mm^2, however, it was possible to obtain more consistent results. By varying the stress range applied to the springs their endurance could be measured and used to construct S/N curves.

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

3.2 Mechanical Testing

Tensile and torsional data have been produced in an effort to obtain a better understanding of the various factors and mechanisms affecting the fatigue resistance of springs after ageing.

3.2.1 Tensile Testing

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

3.2.2 Torsion Testing

Torsion testing was carried out on one of two testing machines, dependant upon the wire diameter.

The 4 mm diameter wire having a gauge length of 400 mm (100d) was tested on a Tinius Olsen 84.7 N m (750 lbf in) capacity multirange, torsion testing machine. The 1.6 mm wire was tested on a vertical Amsler torsion testing machine with a maximum capacity of 5.6 N m (50 lbf in) (Fig. 9.).

3.2. Reverse Bend and Wrapping Tests

Reverse bend and wrapping tests were carried out on the supplied wire in accordance with those specified in D.T.D. 5086 clauses 8.1.2 and 8.1.3.

4. RESULTS

Table I gives the chemical composition of the wires and their nominal diameters, and for comparison purposes the specification analysis for D.T.D. 5086 is shown in Table II.

The design data for the test springs are recorded in Table III.

The results of the fatigue tests are presented as S/N curves in Figs. 1 to 6.

Results from the broken springs were analysed statistically to provide the appropriate regression line and to determine whether the correlation coefficient provided a significance of at least 95%. All data provided a significance greater than 99%.

The fatigue strengths at 10^7 cycles for the various initial stress levels employed are plotted as modified Goodman diagrams in Figs. 7 and 8, and for convenience the results are shown in Table IV.

Table V and VI give the tensile data obtained, for both wire sizes. The torsion results obtained for both wire sizes are presented in Table VII.

Table VIII shows the comparative spring fatigue data of other stainless specifications. The various fatigue, tensile and torsion ratios obtained are given in Tables IX and X.

Table XI and Fig. 10 show the change in U.T.S. on ageing both sizes of wire at temperatures in the range 460-500°C. Figs. 11 a, b and c illustrate various non-metallic inclusions found in the wire.

Confirmation of the constituents of the inclusions present in the wire, shown in Table XII, was obtained from electron probe micro-analysis.

Figs. 12 a, b and c show typical etched structures.

Figs. 13 a, b and c show typical fatigue fraotures at high, intermediate and low fatigue lives of unpeened springs manufactured from 4 mm diameter wire.

5. DISCUSSION

5.1 Fatigue Properties

5.1.1 Fatigue Strength

It can be seen from the modified Goodman diagrams in Fig. 7 and from the data in Table VIII, that shot peened springs made from the 4 mm diameter British 17-7 PH quality wire, possessed similar fatigue properties, at initial stress levels of 77 N/mm^2, to shot peened springs made from B.S. 2056(1) and American Armco 17-7 PH(2) quality wires.

The response to shot peening of the 4 mm diameter wire was very impressive, providing an increase in fatigue strength of approximately 70% (at an initial stress level of 100 N/mm^2). Although this value appears very high in comparison to the normal 20% increase for carbon steels, it can be seen from Fig. 7 that springs manufactured from B.S. 2056 quality wire gave an approximate 80% increase in fatigue strength after shot peening (initial stress of 77 N/mm^2).

Springs manufactured from Armco 17-7 PH material resulted in only a 43% increase in fatigue resistance after shot peening, although the unpeened springs appeared to have a much higher fatigue strength than those for the current 17-7 PH material and B.S. 2056 quality.

In general it is not possible to utilise the improvement in fatigue properties of springs obtained by shot peening, if the wire diameter is below approximately 2 mm, since this operation often leads to excessive distortion of the springs' dimensions, therefore the 1.6 mm diameter wire springs in this report were not shot peened. It can be seen from the Goodman diagrams in Fig. 8 that springs made from British 17-7 PH wire had a similar fatigue strength, at 77 N/mm^2 initial stress level, to the American Armco 17-7 PH 1.7 mm diameter wire springs. Sandvik 12R10(3) steels, which are an 18-8 austenitic type, appear to have inferior fatigue properties to both the British 17-7 PH and American Armco 17-7 PH Springs, which may be due to the low solid stress to which the test springs were manufactured.

A comparison of the 17-7 PH springs made from the two wire sizes, indicated that the 1.6 mm unpeened springs had intermediate fatigue properties falling between the 4 mm peened and unpeened springs.

A general comparison between the 17-7 PH quality springs and those from carbon steels of 4 mm diameter wire, has proved very interesting, the shot peened 17-7 PH springs possessing better fatigue properties than shot peened springs manufactured from S202(4) or S203(5) materials viz:-

QUALITY	WIRE DIAMETER	SURFACE CONDITION	FATIGUE LIMIT N/mm^2 (INITIAL STRESS 100 N/mm^2)
S202	4 mm	Shot Peened	690 (44.7 $tonf/in^2$)
S203	4 mm	Shot Peened	750 (48.6 $tonf/in^2$)
17-7 PH	4 mm	Shot Peened	840 (54.4 $tonf/in^2$)

Broken springs from most of the tests undertaken in this investigation were examined, with a view to obtaining a pattern in fatigue failures from identical springs tested at different stress levels.

5.1.2 Examination of Springs Manufactured from 4 mm Diameter Wire

Examination of the unpeened springs showed all failures to initiate at the inside of the coil, this being the point of maximum stress. Almost every failure followed the general pattern of helical spring failures, by commencing at the inside of the spring and propagating in the direction of the resultant force, which is at 45° to the wire axis. Closer examination of failure showed the more highly stressed springs, which had shortened fatigue lives, to fail with a characteristic 45° crack, initiating on the inside of the spring followed by crack propagation in a longitudinal manner along the wire (Fig. 13 c).

At an intermediate life failure paths were observed which contained an initial 45° failure, followed by a step formation as the crack tended to propagate both longitudinally and at 45° (Fig. 13 b).

The characteristic modes of failure observed during the testing programme are influenced by three major factors:-

(i) Surface.
(ii) Directionality of the tempered martensite.
(iii) Inclusion content.

There is ample evidence to confirm that fatigue properties are very sensitive to surface condition, microstructure, and impurities.

However, the most significant contribution to the various mechanisms of fracture seen at different stress levels is undoubtedly the high concentration of alumina inclusions.

Non metallic inclusions such as Al_2O_3 should be avoided due to the very high stress concentrations existing around each inclusion. It is, however, very difficult to determine the quantitive loss in fatigue life due to Al_2O_3, because much depends on the size, shape, location and orientation relative to the direction of the applied load.

One important feature of Al_2O_3 inclusions is their ability to segregate, usually towards the top of ingots, and hence introduce localised inferior properties, and thus care should be taken in deciding at which stage aluminium should be added to the melt.

Thus, in order that a more detailed examination of the influence of inclusions can be made, it will be necessary to consider straight torsion bars in the absence of stress raisers.

The initial fatigue crack resulting from torsional stressing can occur in either one or two planes of maximum shearing stress which are parallel and perpendicular to the axis of the bar. This initial crack will progressively grow until it causes a sufficient stress concentration to initiate a tensile stress crack at 45° to the bar axis, which in turn propagates along planes of weakest stress, until the remaining section is insufficient to support the applied load and fails almost instantaneously.

However, with helical compression springs, in addition to torsional stress, bending stresses are present on the inside of the coil, producing a material condition which is even more sensitive to material imperfections; as a result helicoidal fractures occur a approximately 45^{o} to the wire axes (Fig. 13 c).

When stress raisers are present in the form of inclusions, initial cracking will occur, and further crack growth will be influenced by localised stress concentrations around each inclusion and by the response of neighbouring planes to the applied stress. However, in most cases, alumina inclusions induce such high stress concentrations, that inevitably crack propagation follows the most convenient inclusion path at some stage of the crack growth.

With the springs in question it would therefore seem reasonable to conclude that highly stressed springs (short life) have a choice of either propagating in the conventional manner or propagating from inclusion to inclusion.

However, as the stress is reduced, suitably oriented shear planes, which would normally submit to the applied stress, are relieved at certain stages of crack growth due to the presence of alumina inclusions.

Finally at lower stress levels, inclusion characteristics play a major role and directly influence total propagation (Fig. 13 a).

Examination of Springs Manufactured from 1.6 mm Diameter Wire

Due to the many variations in spring failures from this smaller diameter wire, it was not possible to detect a pattern in the results.

However, characteristic failures which were observed on the 4 mm wire at various stress levels were seen on this smaller wire, but there did not appear to be any consistency in failure characteristics.

A survey of the positions of failure on the smaller springs indicated that there was a significant relationship between failure position and spring life. Springs possessing short fatigue lives, i.e. between 1 and 5 million cycles, showed fractures to occur at the centre coil. However, springs having lives of 8, 9 and 10 million cycles showed failure to occur at the first coil, and those possessing fatigue lives close to the fatigue limit did not appear to fail prematurely due to fretting as might be expected due to spring relaxation.

Many longitudinal fatigue cracks were observed on most of the springs, these were not continuous but appeared as intermittent lines leading from the failure zone, along the inside radius.

5.2 Mechanical Properties

In order to make a full assessment of the 17-7 PH material for the application of springs the various mechanical properties will be compared.

5.2.1 Tensile Strength

From Table VI it can be seen that the actual tensile strength of the 4 mm diameter wire in the as-drawn condition varied between 1347 and 1438 N/mm^2 (87.2 to 93.1 tonf/in^2), being at the bottom of the D.T.D. 5086 specified tensile range i.e. 1359 to 1699 N/mm^2 (88 to 110 tonf/in^2). The response to ageing at 480°C for one hour, was very low, producing tensile strengths in the range 1532 to 1554 N/mm^2 (99.2 to 100.6 tonf/in^2) compared with the D.T.D. 5086 range of 1699 to 2008 N/mm^2 (110 to 130 tonf/in^2). An unusual feature was observed during tensile testing the 4 mm 'as-drawn' wire, where at approximately 95% of the tensile strength, large amounts of extension were observed due to regions of localised necking along the test specimens.

In order to determine an adequate explanation, sections of wire were taken from these areas and examined under the microscope. In the unetched condition, the areas of necking had a similar size and distribution of inclusions to areas where necking did not appear.

In the etched condition, nothing unusual was observed although in general the structure appeared slightly more coarse where necking occurred. This would indicate that as with normal 18-8 stainless steels, areas of necking were due to the material not reaching maximum strain hardening, thereby remaining slightly softer and more ductile.

This effect was not observed on 1.6 mm diameter wire.

The response to ageing, as measured by the tensile proof stresses, appeared more marked than when measured by the ultimate tensile strength. Increases of the order of 23, 22 and 24% were obtained for the 0.1, 0.2 and 0.5% proof stresses.

Due to the poor response of both wire sizes on ageing, a series of tests was carried out at temperatures around the recommended 480°C, to determine whether under or overageing had occurred, thereby producing the results obtained.

Table XI and Fig. 10, show the effect of ageing temperature on tensile strength.

It will be seen for the 4 mm diameter wire that the maximum strength was reached at 490°C, this being 1549 N/mm^2 (100.3 $tonf/in^2$) as opposed to 1543 N/mm^2 (99.9 $tonf/in^2$), at 480°C.

This increase in U.T.S. can be considered as insignificant, and in fact the maximum change in U.T.S. between 460°C and 500°C, was only 51 N/mm^2 (3.3 $tonf/in^2$). From examination of the 1.6 mm diameter wire, it would appear as before, that the maximum strength of 1858 N/mm^2 (120.3 $tonf/in^2$) was after ageing at 490°C. However, the maximum change in U.T.S.

between 460 and 500°C was only a mere 29 N/mm^2 (1.9 $tonf/in^2$).

It is evident therefore that the accurate control of ageing temperature (±5°C) at 480°C is not necessary, and the problem of response to ageing is not due to incorrect ageing temperature.

In the case of 17-7 PH the process of precipitation hardening has a two-fold effect:-

(a) It stress relieves and tempers martensite, thereby providing toughness, ductility and corrosion resistance, due to reduction in internal strain energy.

(b) It provides additional hardening by precipitation of intermetallic compounds of nickel aluminium.

Because of these two opposing factors, the ductility of this type of material tends to remain constant, and in the case of the 4 mm wire an increase of 2% in reduction of area was observed, after ageing (see Table VI).

Percentage elongation calculated over a 2 in gauge length produced a fall from 9.6 to 2.8. However, due to the non-uniform properties of the wire resulting from areas of low strain hardening, the elongation figures for as-drawn material will be very high and therefore unreliable.

The more meaningful aged results, however, should be accepted as correct, and thus from these, the as-drawn figures can be predicted as falling in the region of 3-4%. This is born out further by examining the 1.6 mm diameter wire where there was little change in elongation after ageing.

It can be seen from Table V that the as-drawn tensile strength of the 1.6 mm wire was well below specification at approximately 1544 N/mm^2 (100 $tonf/in^2$), the D.T.D. 5086 specified range being 1653 to 1946 N/mm^2 (107 to 126 $tonf/in^2$).

However, the response to ageing was more effective than with the 4 mm wire, providing tensile strengths of the order of 1800 N/mm^2 (118 tonf/in^2), an 18% increase.

The 0.1% proof stress was greatly increased as a result of ageing, producing a 26% increase in strength, while the 0.2% PS produced only 18%.

The reduction in area of the 1.6 mm wire fell by approximately 2% on ageing, the exact opposite of the larger wire size.

The elongation % remained steady at approximately 3%. after ageing.

5.2.2 Fatigue Ratios

In general the fatigue strength of an unpeened spring at zero initial stress will be approximately 45% of the ultimate tensile strength of the wire from which it is made. In the case of 17-7 PH material, the 4 mm diameter shot peened material gave a fatigue ratio of .50 as opposed to .27 in the unpeened condition (i.e. fatigue ratio = $\frac{\text{Fatigue strength}}{\text{U.T.S.}}$).

The 1.6 mm diameter springs, however, which were in the unpeened condition, showed a low .30 similar to unpeened springs made from 4 mm diameter wire.

5.2.3 Tensile Ratios

Table X shows the effect on the tensile ratios of ageing 4 mm and 1.6 mm diameter wire.

Ageing induced a 12% increase in the 0.1% Proof Stress ratio (i.e. PS/UTS) of the 4 mm diameter wire. An increase of 9% in the 0.2 PS ratio was followed by an 11% rise in the 0.5% PS.

The effect of ageing on the 1.6 mm wire was not as marked providing only 7% and 1% increases for the 0.1 and 0.2% PS ratios.

5.2.4 Torsional Strength

Table VII gives a clear representation of the variation in static torsional properties of the two wire sizes.

The 4 mm as-drawn wire revealed a mean maximum torsional shear stress of 1186 N/mm^2 (7[illegible].8 tonf/in^2). After ageing the maximum stress increased by 16% to 1371 N/mm^2 (88.8 tonf/in^2).

The maximum shear strength to UTS ratio was 0.86 and 0.89 for as-drawn and aged materials, respectively, these figures being in general agreement with those obtained for other spring wire qualities.

The 1.6 mm wire in the as-drawn condition gave a maximum shear strength of 1220 N/mm^2 (79.0 tonf/in^2). After ageing this value increased by 10% to 1339 N/mm^2 (86.7 tonf/in^2). Again the shear strength to UTS ratio was of the order of 80% in the as-drawn condition, but fell to 73% in the aged condition.

The response to ageing on the torsional proof stresses of the 4 mm wire proved very interesting, realising increases of 57, and 44% for the 0.1 and 0.2% proof stresses. The 1.6 mm wire size showed 23, 25 and 21% increases for 0.1, 0.2 and 0.5% proof stresses. Here again this factor of greater strain hardening on the smaller wire size would account for the lower values.

5.2.5 Torsional Ratios

Table X shows the effect of ageing on the proof stress-maximum shear stress ratios. The 4 mm diameter wire showed higher increases than the tensile ratios of the order of 30% as opposed to approximately 10%. The smaller diameter wire again did not respond as expected, only increasing by approximately 12%.

Torsional proof stress-tensile strength ratios are tabulated and give a clear indication of the good torsional properties.

Size	Condition	Torsional Proof Stress/UTS Ratio		
		0.1%	0.2%	0.5%
4 mm	As-Drawn	0.39	0.48	-
4 mm	Aged 480°C - 1hr	0.55	0.62	-
1.6 mm	As-Drawn	0.38	0.45	0.57
1.6 mm	Aged 480°C - 1hr	0.40	0.48	0.58

In general, for spring steel wire a ratio of 0.40 can be expected for the ratio of torsional elastic limit to tensile strength, however, from the results above it can be seen that ratios varied from 0.38 to 0.62, dependant upon proof stress.

It must be stressed, however, that had the wires responded much more to ageing, the results could have changed somewhat.

6.2.6 Twists to Failure

Twists to failure of the 4mm diameter wire in the as drawn condition gave a constant value of 5, and after ageing a remarkable rise to 17 was recorded. This unusual feature can be attributed to non uniform strain hardening as observed when tensile testing as-drawn wire (see 5.2.1). Examination of the as-drawn wire after torsion testing revealed localised twisting of the wire, and hence the results obtained would tend to be low due to a short effective gauge length. As observed when tensile testing aged wire, the phenomenon of localised deformation was absent due to the various ageing mechanisms increasing strain hardening, thereby producing more uniform properties.

In the case of the 1.6 mm diameter wire, no localised deformation was observed on tensile or torsion testing and hence the twist to failure results obtained should be acceptable. The reduction in twists to failure after ageing, follows the pattern observed for other drawn materials and indicates the strengthening mechanism with consequent loss in in ductility.

5.2.7. Reverse Bend and Wrapping Tests

Reverse bend and wrapping tests were carried out as stated in specification D.T.D. 5086, clauses 8.1.2. and 8.1.3. and the results were found acceptable.

5.3 Metallographic Examination

5.3.1. Polishing Procedure

Metallographic samples were prepared by polishing in the usual manner, through lubricated abrasives and wet polishing operations. A final polish using gamma alumina ensured an adequate polish, without extracting particles such as inclusions from the metal surface and thereby causing scratches.

5.3.2. Examination in the Unetched Condition

Examination of the samples in the unetched condition revealed a substantial amount of inclusions. The longitudinal section (Fig. 11a) shows the general distribution of these inclusions. However, deformation had resulted in a breaking up of very brittle inclusions, which ultimately lined up in the direction of working. From Fig. 11b the brittle inclusions can be seen more clearly; the sharp angular faces, and the grey-black colour of the inclusions would tend to suggest that aluminium oxide (Al_2O_3) was present, resulting from the 1% Al added to the steel to assist in the final precipitation hardening process.

Examination of the transverse section (Fig. 11c) showed an even distribution of these inclusions, although the particle clusters can be seen to vary in size quite considerably.

In order to detect more accurately the type of inclusions present, an electron probe microanalysis was carried out on a small longitudinal section of wire polished to 1 μ diamond finish. Three typical inclusions were analysed for the following elements, aluminium, silicon, manganese, magnesium, calcium, titanium, iron, chromium, and sulphur. The micro-analyser was operated at a 25 kilovolt potential, using a 0.1 μA beam current, and mica crystal.

Only aluminium, iron, manganese and chromium were detected within the inclusions. However, due to matrix interference arising from the finite diameter of the electron beam, the last three elements can be ignored. This is supported by the ratio of chromium to iron counts, which is similar to that of the matrix; appreciable amounts of chromium in the inclusions would upset the ratio. Table XII gives the analysis of the three inclusions examined. From the table it can be seen that the large inclusions previously seen under the microscope were aluminium oxide (Al_2O_3).

The process of ageing of these types of steels is totally dependant upon the combination of aluminium and nickel producing an intermetallic compound. In the martensitic condition, the aluminium in these steels is in supersaturated solid solution. Upon heating for precipitation hardening, the aluminium in the martensite is precipitated as a Ni-Al compound, and it is this process that produces the increase in strength.

From examination of the unetched samples, it would appear that the large amount of alumina present was due to the aluminium not entering solution.

Aluminium has a greater affinity for oxygen, than nickel and if allowed, will form Al_2O_3 inclusions, the ultimate effect on strength and fatigue life being as follows:-

(a) The available increase in tensile strength will not be utilised due to the reduced amount of intermetallic precipitates.

(b) The large amount of inclusions will introduce stress raisers and crack nuclei, which could lead to premature failure under fatigue conditions.

(c) The inclusions will cause large amounts of scatter in the fatigue results as previously discussed.

5.3.3. Examination in the Etched Condition

Fig. 12a shows the structure of a longitudinal section of as-drawn wire at a magnification of x 100. Martensite formation in 17-7 PH can be produced by a suitable thermal process or by cold working. In this particular case the martensite seen was produced by heavy deformation of the material, inducing the transformation to martensite along the slip planes where some carbon is deposited in the form of chromium carbides ($Cr_{23}C_6$).

Fig. 12b at x 520 shows more clearly the evidence of deformation, the hard martensite being orientated in the drawing direction, as transformation proceeded.

Higher magnifications above x 1000 are required to show the distribution of carbides within the martensitic structure.

Fig. 12c shows a transverse section, again revealing a martensitic structure. Examination of aged specimens showed a slight tempering of the martensite, and heavy distortion.

The effect of precipitation hardening of the martensite matrix by Ni-Al intermetallic compounds could not be detected by optical microscopy. Electron microscope techniques would be necessary in order to detect this effect.

6. CONCLUSIONS

1. Shot peened springs manufactured from 4 mm diameter 17-7 PH quality wire had an equivalent fatigue strength at lower stress levels to shot peened springs manufactured from B.S. 2056 and Armco 17-7 PH, 2.6 diameter spring steel wire. (Lack of comparative fatigue date prevented assessments at high initial stress levels being made.)

2. Unpeened springs manufactured from 4 mm diameter 17-7 PH quality wire had a similar fatigue strength at low initial stress levels to unpeened springs manufactured from 2.6 mm diameter B.S. 2056 wire, but a lower strength than springs made from Armco 17-7 PH material.

3. Shot peening of springs manufactured from 4 mm diameter 17-7 PH spring wire, produced a 68% increase in fatigue strength.

4. Unpeened springs manufactured from 1.6 mm diameter 17-7 PH quality wire had an equivalent fatigue strength to springs manufactured from Armco 17-7 PH 1.7 mm diameter wire.

7. RECOMMENDATIONS

The disappointing response to ageing of both the 4 mm and 1.6 mm diameter wires was due to the lack of aluminium in solid solution, resulting in a low concentration of aluminium-nickel intermetallic compounds. However, the eventual fatigue properties obtained were good and comparable to other related specifications. If the ageing treatment had been more effective then there may have been a possible further increase in fatigue strength, together with higher tensile and torsional strengths.

The following features could therefore be examined:-

1. The effect of tensile strength after ageing on fatigue life of springs.

2. The influence of steel making practice on the inclusion level of 17-7 PH and its effect on both static and dynamic properties of wire.

3. The effect of vapour blasting and dry honing on the fatigue life of springs made from 1.6 mm diameter wire

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TABLE I ACTUAL CHEMICAL COMPOSITION OF 17-7 PH QUALITY WIRE

Wire Diameter	%C	%Si	%Mn	%S	%P	Ni	Cr	Al
4 mm (0.160 in)	.08	.48	.84	.007	.018	6.8	17.2	1.06
1.6 mm (0.064 in)	.08	.48	.89	.007	.018	6.9	17.6	1.02

TABLE II DTD 5086 SPECIFICATION CHEMICAL ANALYSIS

%C	%Si	%Mn	%S	%P	%Ni	%Cr	%Al
0.09 max	1.0 max	1.0 max	0.025 max	0.035 max	6.5-7.75	16.0-18.0	0.75-1.5

TABLE III SPRING DESIGN DATA

	4 mm Wire		1.6 mm Wire	
	Metric	Imperial	Metric	Imperial
Spring Mean Diameter	26.9 mm	1.05 in	11 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 mm	2.0 in	22 mm	0.9 in
Solid Stress after Grinding and Prestressing	1282 N/mm^2	83.0 tonf/in^2	1459 N/mm^2	94.4 tonf/in^2

TABLE IV FATIGUE DATA FOR SPRINGS MANUFACTURED FROM 17-7 PH QUALITY WIRE

Wire Diameter	Surface Condition	Cycles	Fatigue Strength at an Initial Stress Level of:- 100 N/mm^2 (6.47 tonf/in^2)		500 N/mm^2 (32.4 tonf/in^2)	
			N/mm^2	tonf/in^2	N/mm^2	tonf/in^2
4 mm	Shot Peened	10^6 10^7	1025 840	66.4 54.4	1160 1100	75.0 71.2
4 mm	Unpeened	10^6 10^7	680 500	44.0 32.4	850* 750*	55.0 48.5
1.6 mm	Unpeened	10^6 10^7	975 620	63.1 40.1	1125 1025	72.8 66.4

* Initial Stress reduced to 400 N/mm^2 (25.9 tonf/in^2) due to scatter in results at 500 N/mm^2 (32.4 tonf/in^2)

TABLE V TENSILE DATA FOR 17-7 PH QUALITY WIRE

Wire Diameter	Condition	Ultimate Tensile Strength				Proof Stress						Reduction in Area	Elongation % on 2 in Gauge Length
		As specified in D.T.D. 5086		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	%	
1.6 mm (0.064 in)	As Drawn	1653 1946	107 126	1551	100.4	1334	86.4	1529	99.0	-	-	48.3	3.0
1.6 mm (0.064 in)	As Drawn	1653 1946	107 126	1537	99.5	-	-	-	-	-	-	-	-
1.6 mm (0.064 in)	As Drawn	1653 1946	107 126	1560	101.0	1248	80.8	1510	97.8	-	-	44.3	NIL
Mean Value				1549	100.3	1292	83.7	1519	98.4	-	-	46.4	3.0
1.6 mm (0.064 in)	Aged 480°C-1hr	2008 2317	130 150	1785	115.6	1560	101.0	1768	114.5	-	-	43.8	3.0
1.6 mm (0.064 in)	Aged 480°C-1hr	2008 2317	130 150	1863	120.6	-	-	-	-	-	-	-	-
1.6 mm (0.064 in)	Aged 480°C-1hr	2008 2317	130 150	1846	119.5	1699	110.0	1843	119.3	-	-	44.3	2.0
Mean Value				1831	118.6	1629	105.5	1105	116.9	-	-	44.0	2.5

TABLE VI TENSILE DATA FOR 17-7 PH QUALITY WIRE

Wire Diameter	Condition	Ultimate Tensile Strength				Proof Stress						Reduction in Area %	Elongation % on 2 in Gauge Length
		As Specified in D.T.D.5086		Actual		0.1%		0.2%		0.5%			
		N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	tonf/in	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2		
4 mm (0.160 in)	As Drawn	1359 1699	88 110	1347	87.2	961	62.2	1098	71.1	1299	79.6	47.6	12.0
4 mm (0.160 in)	As Drawn	1359 1699	88 110	1438	93.1	-	-	-	-	-	-	-	-
4 mm (0.160 in)	As Drawn	1359 1699	88 110	1362	88.2	877	56.8	1039	67.3	1203	77.9	45.8	7.5
4 mm (0.160 in)	As Drawn	1359 1699	88 110	1362	88.2	-	-	-	-	-	-	-	-
Mean Value				1377	89.2	919	59.5	1069	69.1	1215	78.7	46.7	9.6
4 mm (0.160 in)	Aged 480°C-1hr	1699 2008	110 130	1532	99.2	1168	75.6	1313	85.0	1529	99.0	47.6	3.5
4 mm (0.160 in)	Aged 480°C-1hr	1699 2008	110 130	1554	100.6	1124	72.8	1291	83.6	1495	96.8	48.5	2.0
Mean Value				1543	100.0	1146	74.2	1302	84.3	1512	98.0	48.0	2.8

TABLE VII TORSION DATA FOR 17-7 PH QUALITY WIRE

Wire Diameter	Condition	Maximum Shear Strength		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 mm (0.160 in)	As Drawn	1208	78.2	611	39.5	737	47.7	-	-	5
4 mm (0.160 in)	As Drawn	1166	75.5	482	31.2	559	36.2	-	-	5
4 mm (0.160 in)	As Drawn	1186	76.8	533	34.5	688	44.5	-	-	5
Mean Values		1186	76.8	541	35.0	661	42.8	-	-	5
4 mm (0.160 in)	Aged 480°C-1hr	1365	88.4	868	56.2	971	62.9	-	-	17
4 mm (0.160 in)	Aged 480°C-1hr	1363	88.2	816	52.9	926	59.9	-	-	17
4 mm (0.160 in)	Aged 480°C-1hr	1388	89.9	868	56.2	971	62.9	-	-	17
Mean Values		1371	88.8	849	55.0	954	61.8	-	-	17
1.6 mm (0.064 in)	As Drawn	1206	78.1	643	41.6	743	48.1	911	59.0	7
1.6 mm (0.064 in)	As Drawn	1233	79.8	542	35.1	663	42.9	851	55.1	8
Mean Values		1220	79.0	593	38.4	703	45.5	881	57.0	7.5
1.6 mm (0.064 in)	Aged 480°C-1hr	1339	86.7	670	43.4	843	54.6	1046	67.7	5
1.6 mm (0.064 in)	Aged 480°C-1hr	1339	86.7	791	51.2	911	59.0	1086	70.3	5
Mean Values		1339	86.7	731	47.3	877	56.8	1066	69.0	5

TABLE VIII COMPARATIVE FATIGUE DATA FOR 10^7 CYCLES

Material	Wire Diameter (mm)	Surface Condition	Fatigue Limit Initial Stress 77 N/mm^2
B.S. 2056	2.6	S/P	800
B.S. 2056	2.6	U/P	448
Armco 17-7 PH	2.6	S/P	840
Armco 17-7 PH	2.6	U/P	590
Armco 17-7 PH	1.7	U/P	590
Sandvik 12R10 (18-8)	2.0	U/P	425

TABLE IX THE FATIGUE RATIO OF HELICAL COMPRESSION SPRINGS MADE FROM PRECIPITATION HARDENED 17-7 PH WIRE

Wire Diameter	Surface Condition	Fatigue Ratio $\frac{\text{Fatigue Limit At Zero Initial Stress}}{\text{UTS}}$
4 mm (0.160 in)	Unpeened	0.27
4 mm (0.160 in)	Shot Peened	0.50
1.6 mm (0.064 in)	Unpeened	0.30

TABLE X THE TENSILE AND TORSIONAL RATIOS OF 17-7 PH WIRE

Wire Diameter	Condition	Ultimate Tensile Strength		Tensile P.S.-UTS Ratio			Maximum Shear Stress		Torsional P.S.-M.S.S. Ratio		
		N/mm^2	tonf/in^2	0.1%	0.2%	0.5%	N/mm^2	tonf/in^2	0.1%	0.2%	0.5%
4 mm (0.160 in)	As-Drawn	1377	89.2	0.66	0.77	0.88	1186	76.8	0.46	0.56	-
4 mm (0.160 in)	Aged 480°C-1hr	1543	100.0	0.74	0.84	0.98	1371	88.8	0.62	0.70	-
1.6 mm (0.064 in)	As-Drawn	1549	100.3	0.83	0.98	-	1220	79.0	0.49	0.58	0.72
1.6 mm (0.064 in)	Aged 480°C-1hr	1839	118.6	0.89	0.99	-	1339	86.7	0.55	0.65	0.80

TABLE XI THE CHANGE IN UTS ON AGEING 17-7 PH WIRE

Temperature	Tensile Strength			
	4 mm (0.160 in) Diameter		1.6 mm (0.064 in) Diameter	
°C	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2
460	1531	99.16	1829	118.40
460	1531	99.16	1829	118.40
Mean Value	1531	99.16	1829	118.40
470	1543	99.90	1829	118.40
470	1543	99.90	1833	118.70
Mean Value	1543	99.90	1831	118.55
480	1535	99.40	1829	118.40
480	1551	100.40	1844	119.40
Mean Value	1543	99.90	1836	118.90
485	1549	100.30	1849	119.70
485	1547	100.16	1833	118.70
Mean Value	1548	100.23	1841	119.20
490	1543	99.90	1858	120.30
490	1555	100.70	1858	120.30
Mean Value	1549	100.30	1858	120.30
500	1504	97.04	1829	118.40
500	1509	97.70	1833	118.70
Mean Value	1507	97.55	1831	118.55

TABLE XII ELECTRON PROBE MICRO ANALYSIS OF THREE INCLUSIONS

Analysis	Inclusion No. 1	Inclusion No. 2	Inclusion No. 3
Aluminium Oxide (Al_2O_3)	72.7%	92.5%	92.0%
Silicon Oxide (SiO_2)	-	-	-
Magnesium Oxide (MgO)	-	-	-
Calcium Oxide (CaO)	-	-	-
Titanium Oxide (TiO_2)	-	-	-
Iron (Fe)	22.3%	6.8%	6.8%
Chromium (Cr)	4.6%	0.7%	0.9%
Manganese (Mn)	0.4%	0.1%	0.3%
Sulphur (S)	-	-	-

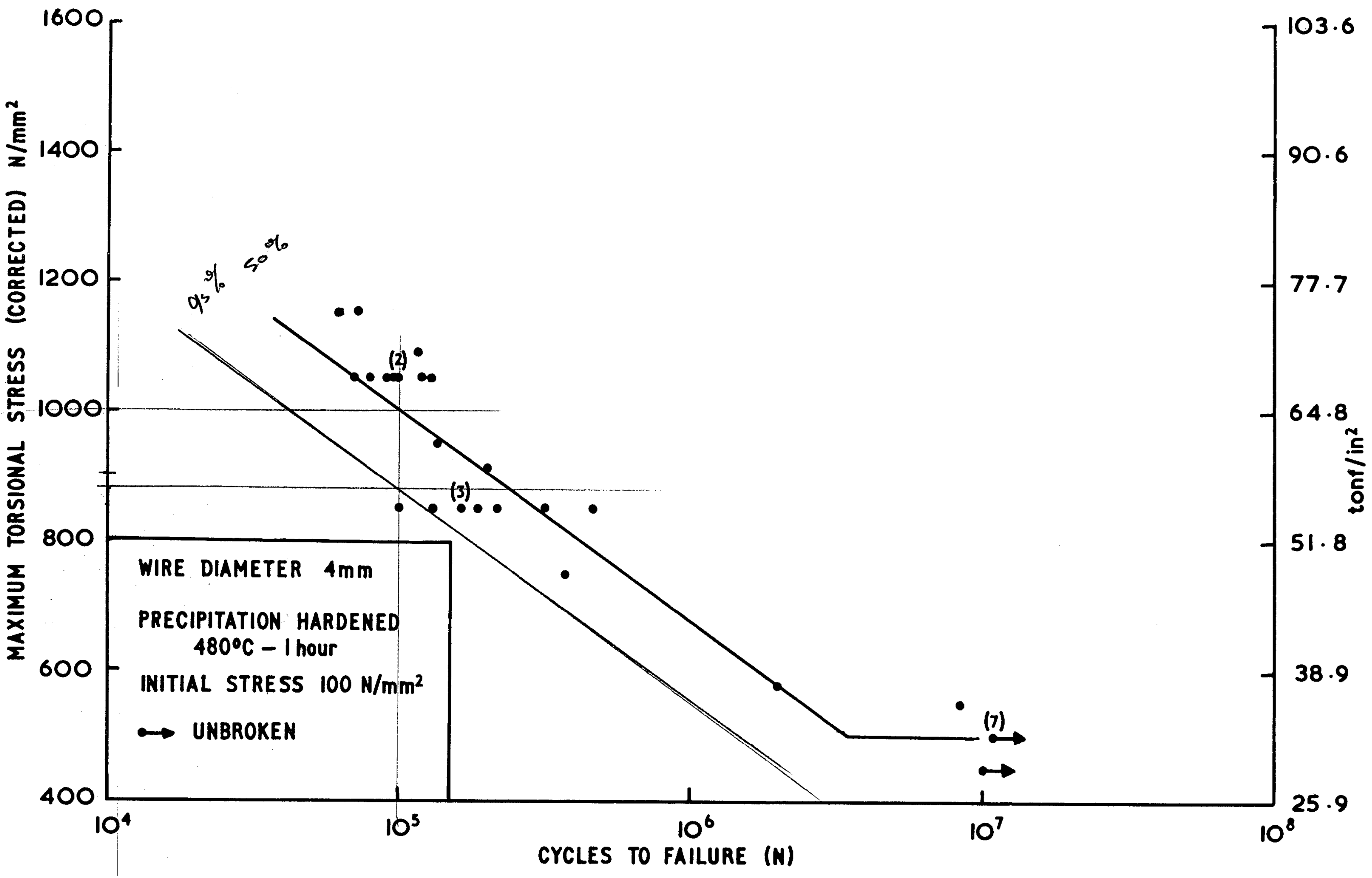


FIG. 1. S/N CURVE FOR 17-7 PH UNPEENED SPRINGS

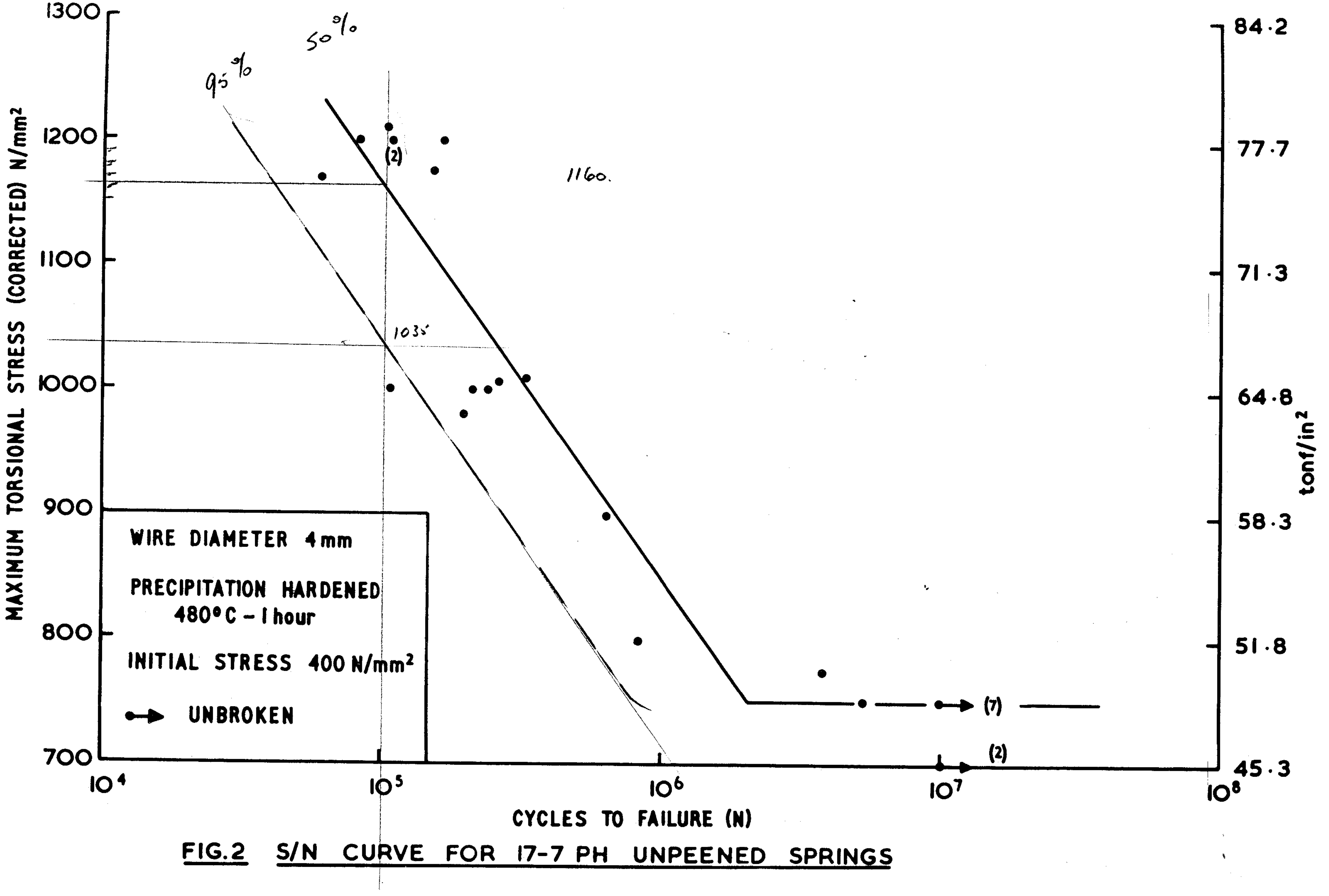


FIG.2 S/N CURVE FOR 17-7 PH UNPEENED SPRINGS

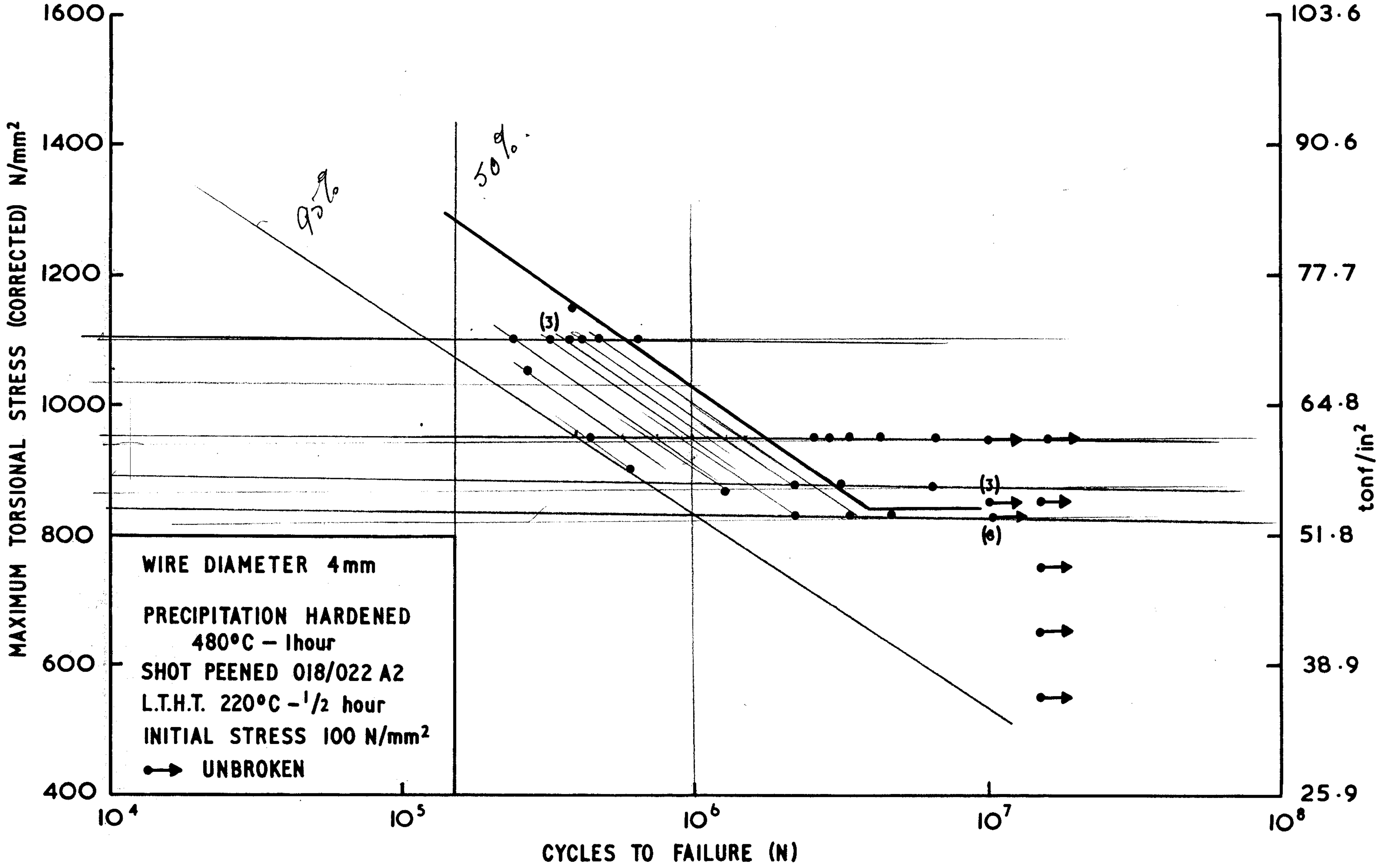


FIG. 3. S/N CURVE FOR 17-7 PH SHOT PEENED SPRINGS

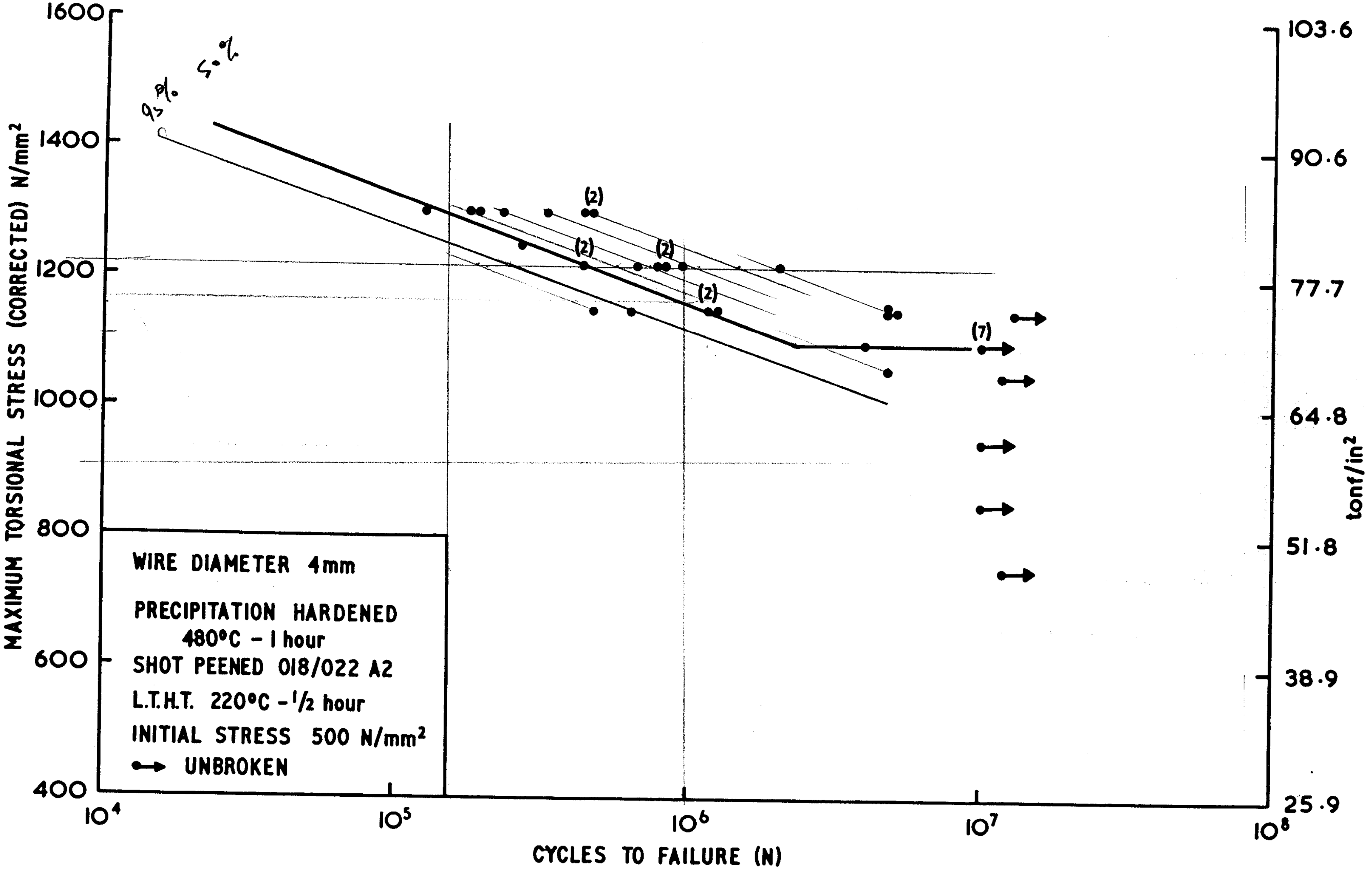


FIG. 4. S/N CURVE FOR 17-7 PH SHOT PEENED SPRINGS

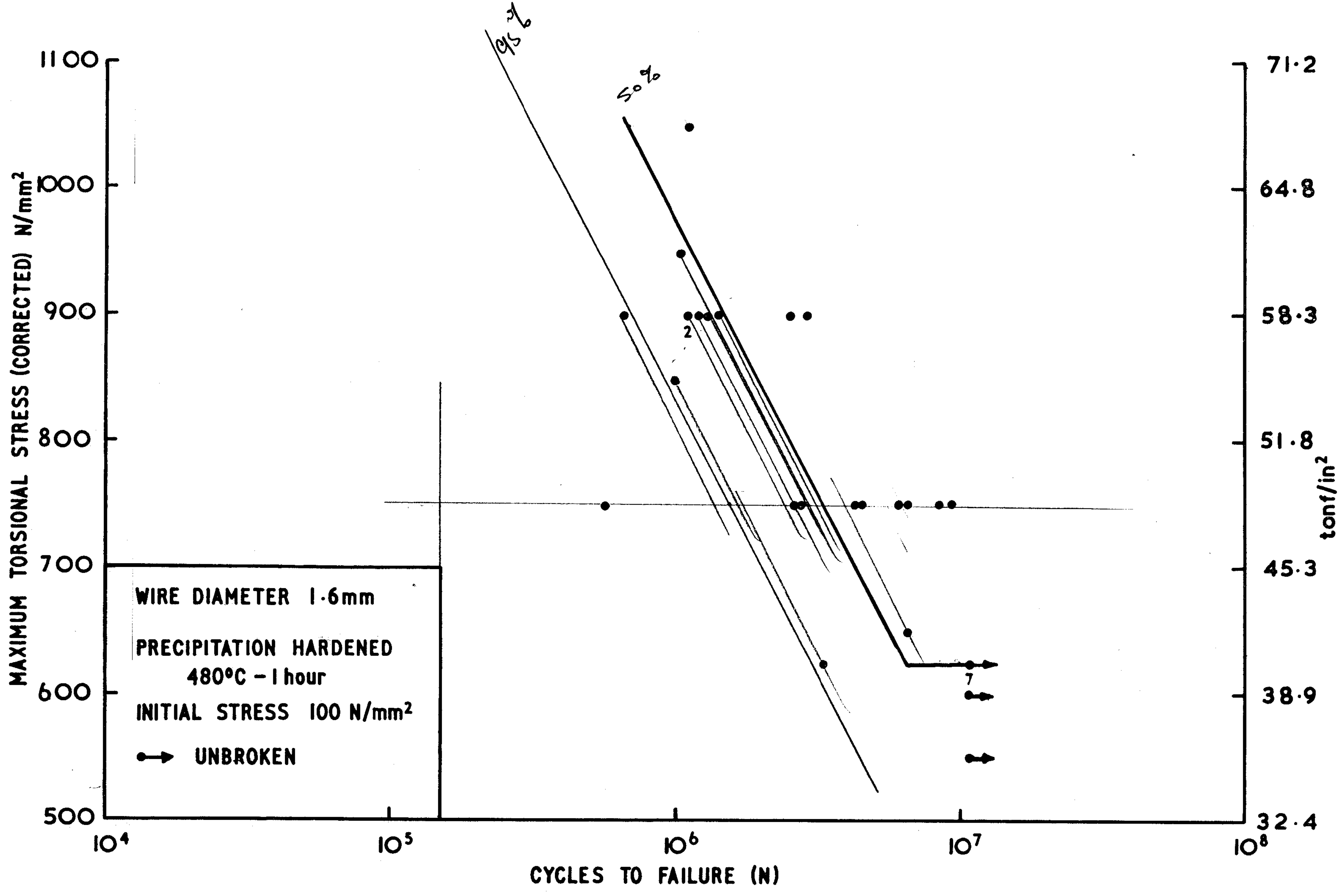


FIG. 5. S/N CURVE FOR 17-7 PH UNPEENED SPRINGS

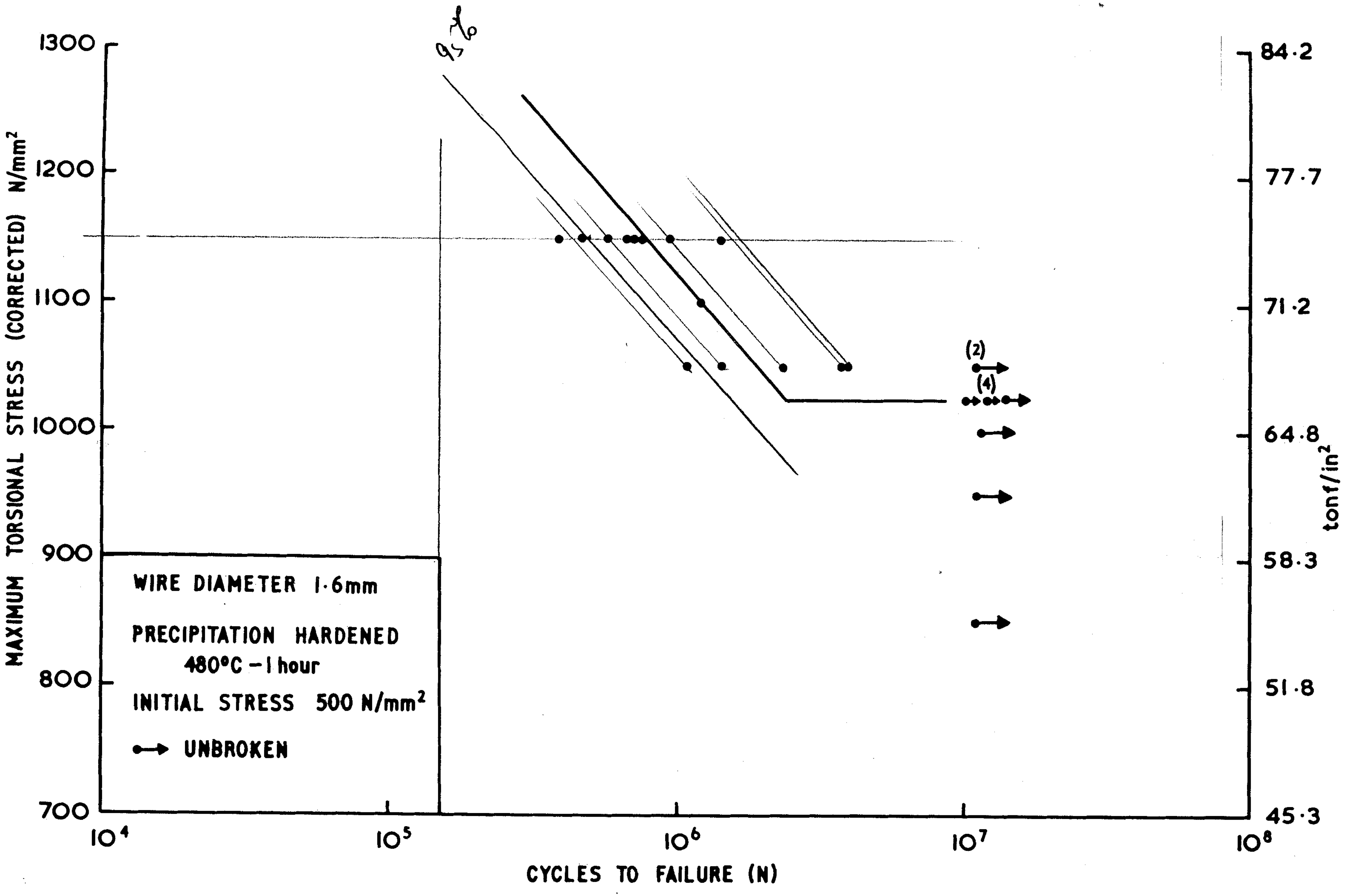


FIG. 6. S/N CURVE FOR 17-7 PH UNPEENED SPRINGS

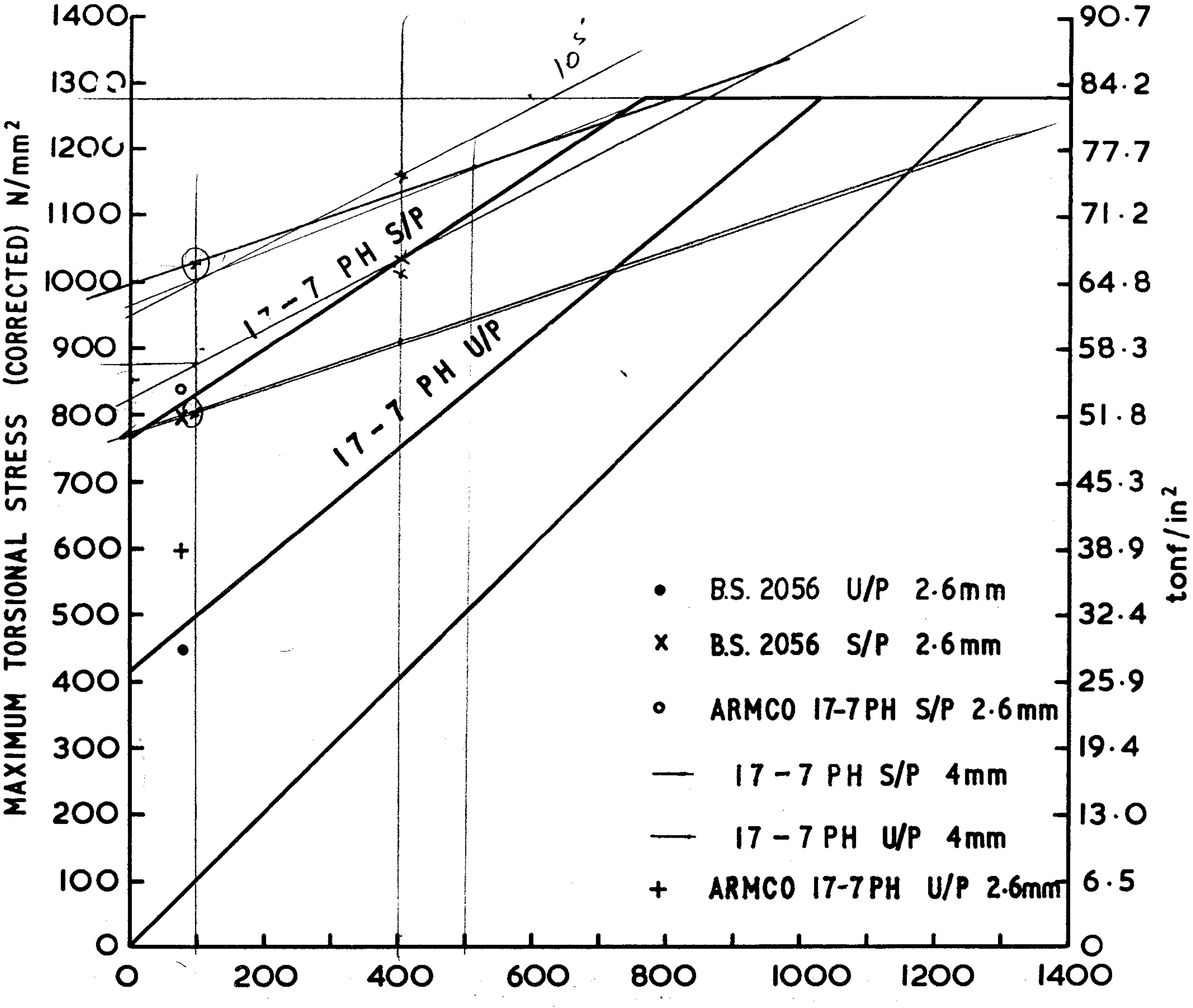


FIG. 7 MODIFIED GOODMAN DIAGRAM FOR 10^7 CYCLES

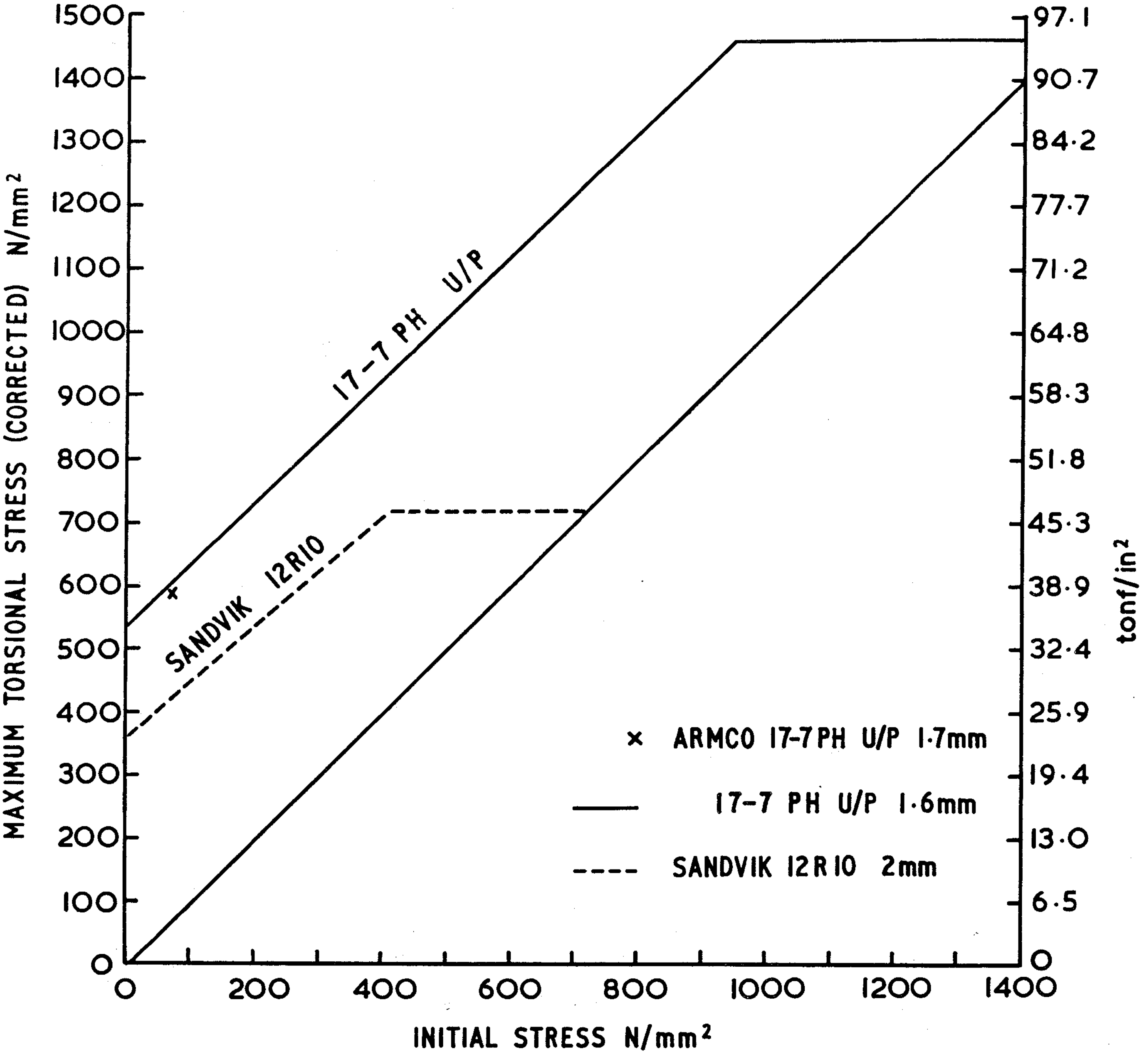


FIG. 8 MODIFIED GOODMAN DIAGRAMS FOR 10^7 CYCLES

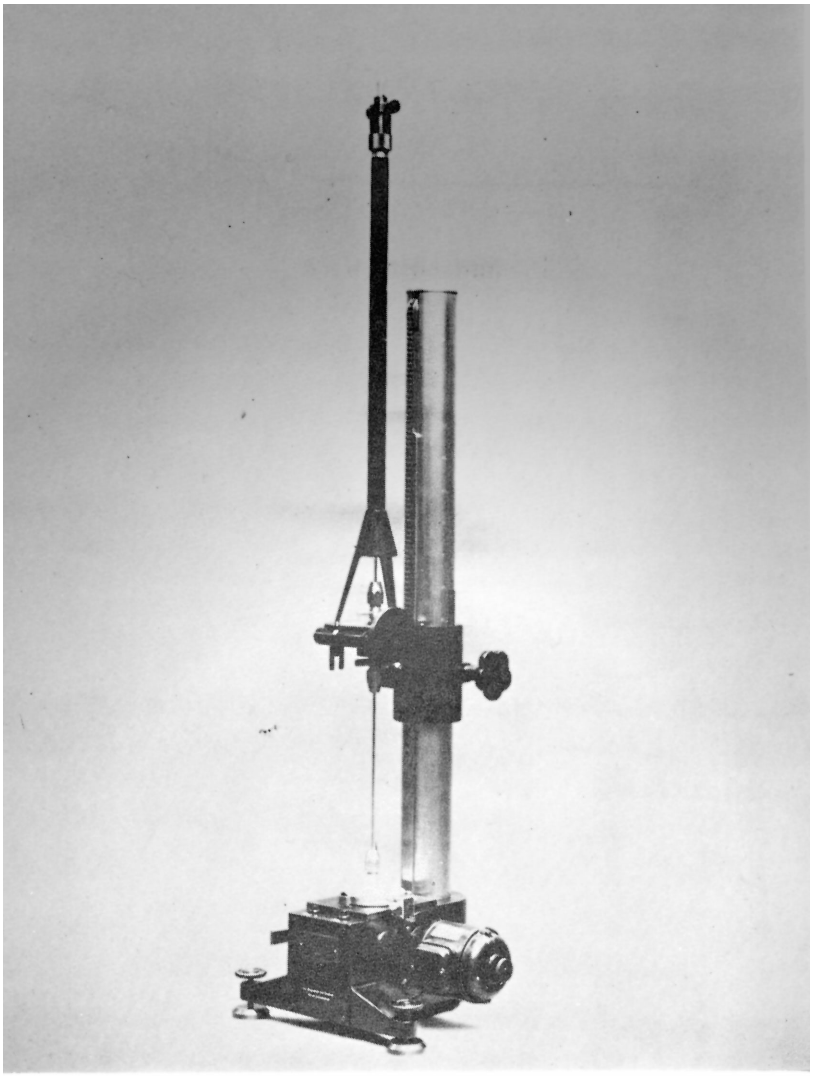


FIG. 9. AMSLER 5.6 Nm TORSION TESTING MACHINE

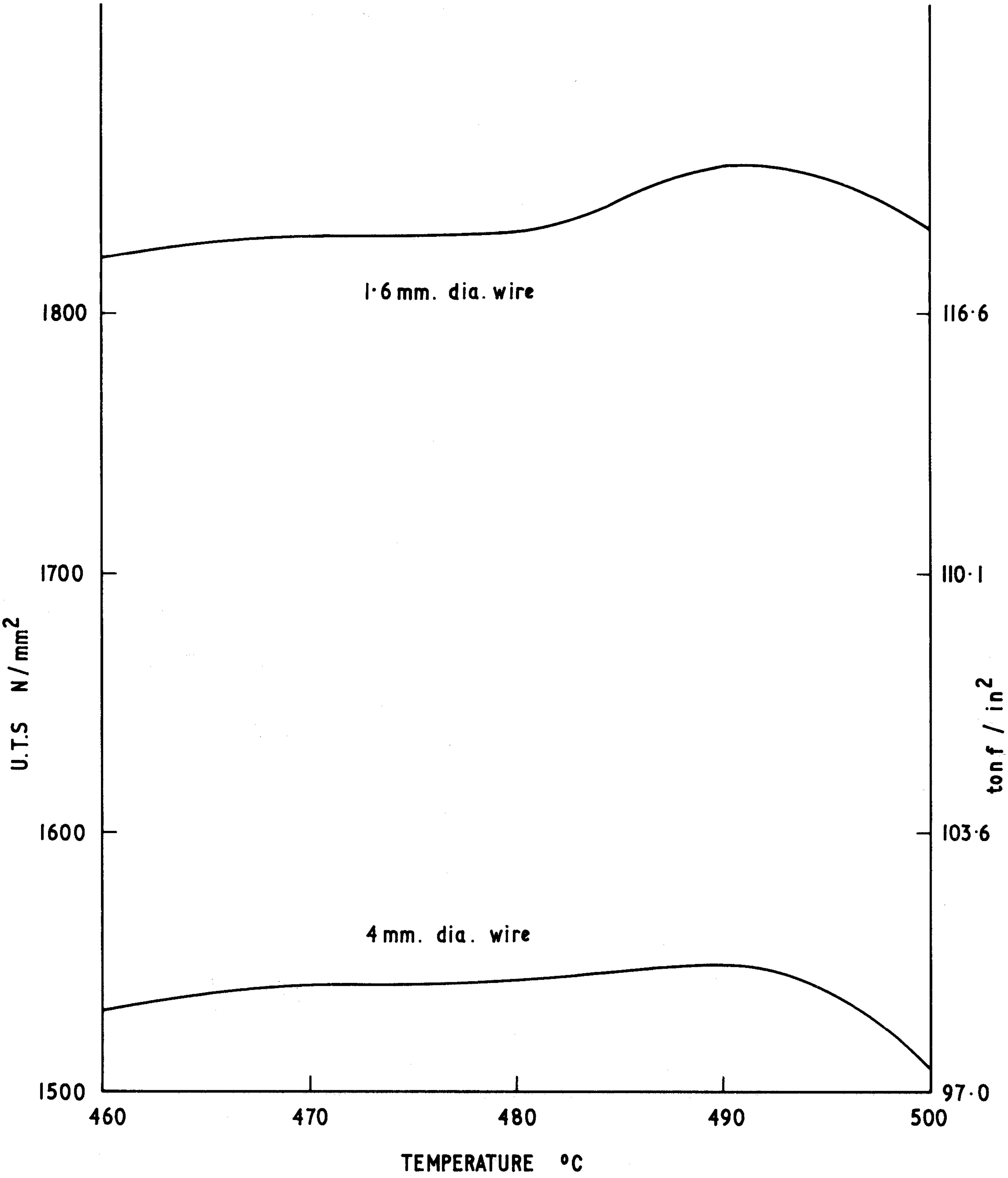


FIG. 10. THE EFFECT OF AGEING TEMPERATURE ON THE U.T.S. OF 17-7 PH QUALITY WIRE

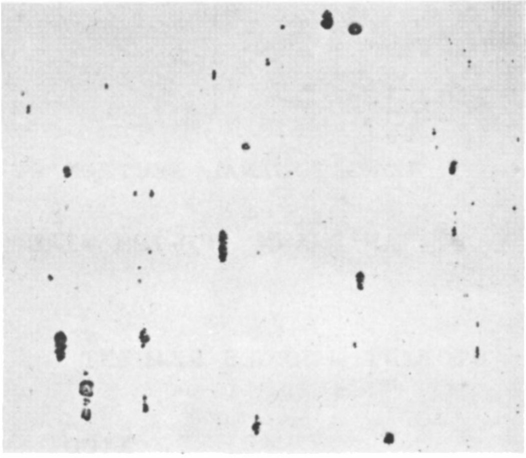


FIG. 11a X100

LONGITUDINAL SECTION
OF 17-7PH WIRE

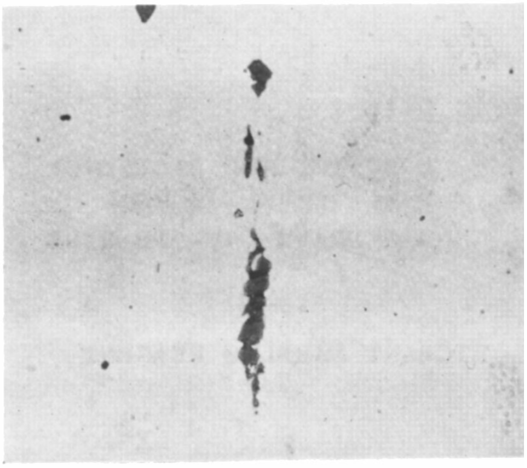


FIG. 11b X520

LONGITUDINAL SECTION
OF 17-7PH WIRE

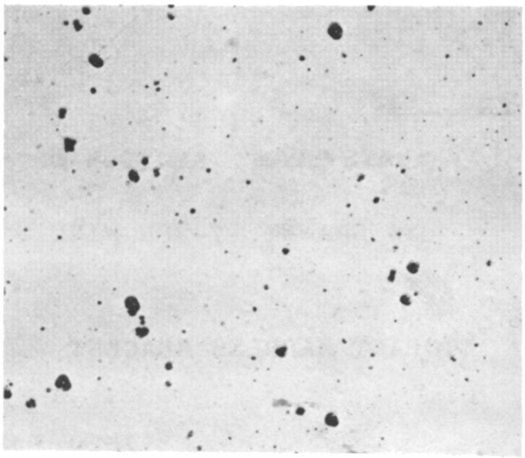


FIG. 11c X100

TRANSVERSE SECTION
OF 17-7PH WIRE

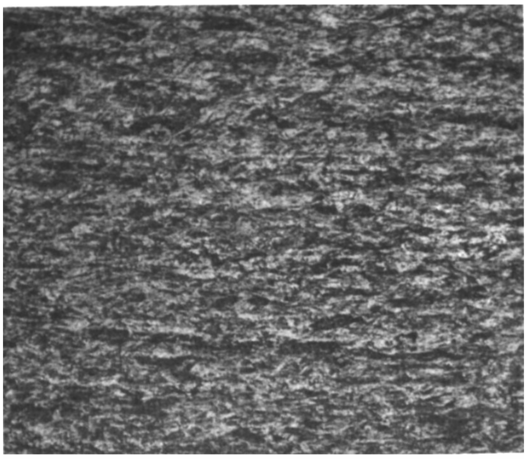


FIG. 12a X100

LONGITUDINAL SECTION OF
AS DRAWN 17-7PH WIRE
ETCHANT MARBLES REAGENT

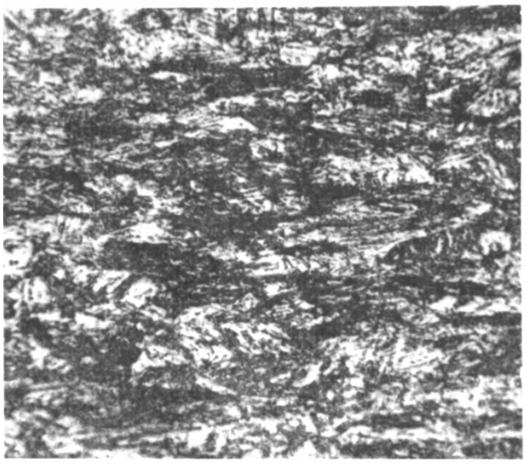


FIG. 12b X520

LONGITUDINAL SECTION OF
AS DRAWN 17-7PH WIRE
ETCHANT MARBLES REAGENT

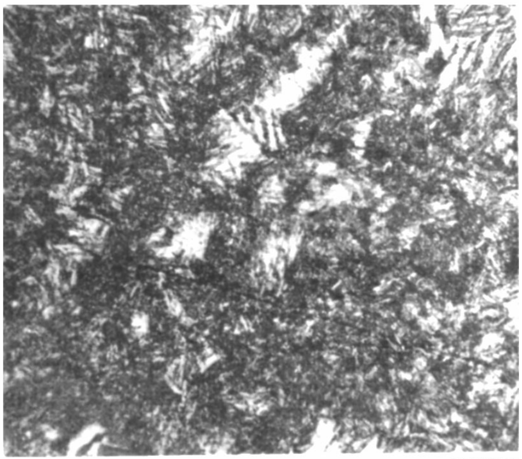
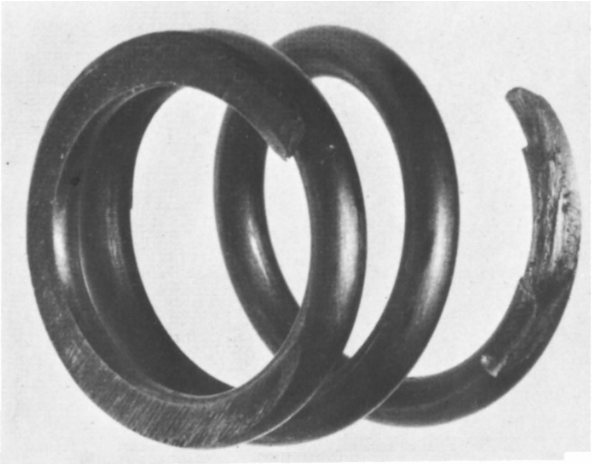
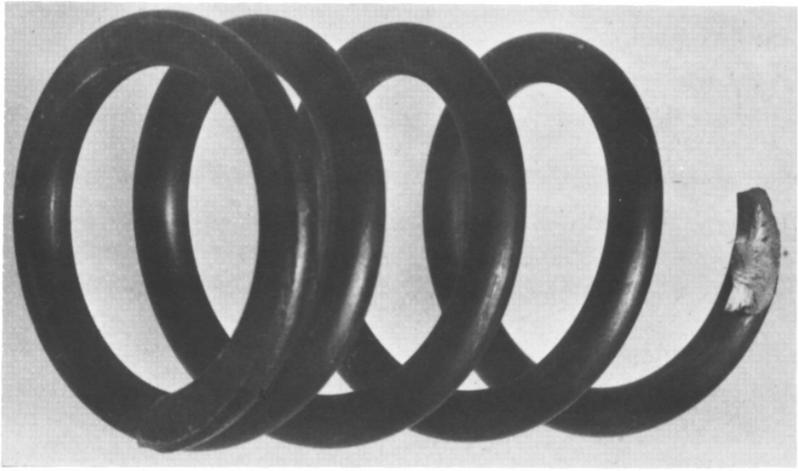


FIG. 12c X520

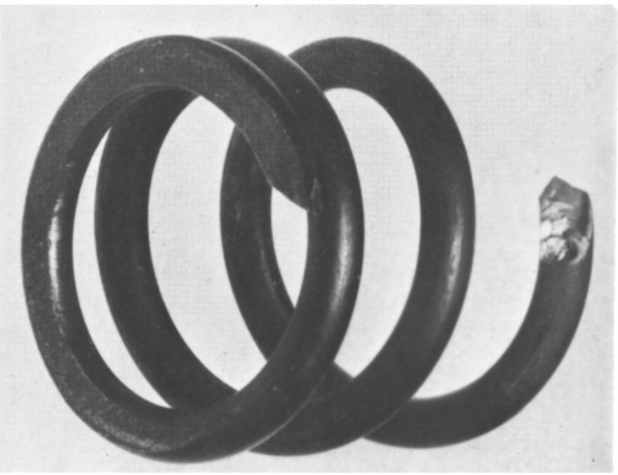
TRANSVERSE SECTION OF
AS DRAWN 17-7PH WIRE
ETCHANT MARBLES REAGENT



a. HIGH FATIGUE LIFE



b. INTERMEDIATE FATIGUE LIFE



c. LOW FATIGUE LIFE

FIG. 13 X2

TYPICAL FATIGUE FRACTURES OF UNPEENED SPRINGS MANUFACTURED FROM 4mm DIAMETER 17-7PH SPRING WIRE