THE SPRING RESEARCH ASSOCIATION

THE PROPERTIES OF ULTRA HIGH STRENGTH CARBON STEEL WIRE AND SPRINGS

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SUMMARY

The influence of low temperature heat treatment on the mechanical properties of U.H.T. 2 and 3 quality wire has been investigated and it has been shown that by treatment within the range 175 to 225°C, considerable improvements in the properties can be obtained.

The effect of stress relieving unpeened U.H.T.3 springs after coiling has been determined and it was found that heat treatment at 400°C gave optimum fatigue performance. Any heat treatments carried out after shot peening had to be limited to 200°C; higher temperatures had an adverse effect on fatigue resistance of shot peened springs.

Modified Goodman diagrams have been produced for unpeened and shot peened springs; they show the fatigue properties of U.H.T.3 springs to be similar to those of springs manufactured from BS 1408C and D wires.

The stress-temperature relaxation behaviour of U.H.T.3 springs was superior to that of BS 1408 springs.

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9. FIGURES

THE PROPERTIES OF ULTRA HIGH STRENGTH CARBON STEEL WIRE AND SPRINGS

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1. INTRODUCTION

The combination of improved steel making practice and hence the quality of rolled rod, and stringent quality control by the wire-drawer has recently led to the introduction in this country of patented cold drawn wires possessing tensile strengths in excess of those currently available from music wires to BS 1408 M. This development is of immediate interest to the spring maker, in view of the continuing demand for springs for service at higher and higher operating stresses. For springs operating at higher working stresses, wire of higher strength is required in order to overcome the problems of excessive "set-down" in service. The use of material of higher tensile strength could, at the same time, lead to improvements in the fatigue resistance of such springs. It has been shown previously(1) that increasing the tensile strength of BS 1408C and D wire from Range 1 to Range 3 gives some improvement in the fatigue strength of springs.

This report describes the work undertaken by the Association to measure the static mechanical properties of ultra high tensile strength wire having a nominal diameter of 3.15 mm. The influence of low temperature heat treatment on these properties has been investigated, as well as the fatigue resistance of both unpeened and shot peened springs coiled from these wires. A study of the stress temperature relaxation behaviour has also been made.

2. MATERIAL

Two consignments of wire having a nominal diameter of 3.15 mm received from the wire manufacturers were designated U.H.T.2 and U.H.T.3. For wire of this size, the manufacturer's tensile strength specifications are:

Grade	N/mm^2
U.H.T.2	1930-2170
U.H.T.3	2010-2250

The composition of each coil of wire is shown in Table I.

3. MECHANICAL PROPERTY TESTS ON WIRE

The full tensile properties of both U.H.T. quality wires were measured both in the as-received condition and also after various low temperature heat treatments, up to a maximum temperature of 400°C. The duration of heat treatment was in all cases ½ hour. The results obtained for U.H.T.2 and U.H.T.3 are presented in Table II and Table III respectively and are also shown graphically in Figs. 1 and 2.

The torsional properties of each wire quality were also determined, both in the as-received condition and also after a low temperature heat treatment which, according to the tensile property data, gave the maximum improvement in elastic properties. It has been found previously that the maximum increase in elastic properties, both in tension and torsion, occurs at the same temperature; it was therefore unnecessary to carry out a complete survey of the properties in torsion over the whole temperature range.

with patented cold drawn carbon steel wires of high tensile strength, strain aging the material, by low temperature treatment, can often lead to a marked loss in torsional ductility. For this reason, the number of twists to failure after various heat treatments has been determined.

The torsional properties for the two materials are given in Tables IV and V and the effects of low temperature heat treatment on the number of twists to failure are illustrated in Fig. 3.

4. PROPERTIES OF SPRINGS

4.1. Spring Design and Manufacture

Test springs were hand coiled to the following design:

Wire diameter : 3.15 mm
Mean coil diameter : 25 mm
Spring index : 8
Total coils : 5.5
Active coils : 3.5
Free length : 49 mm
Solid stress (after prestressing) : 1300 N/mm^2
Ends closed and ground.

Initial coiling and prestressing trials were designed to produce a spring having a solid stress of 70% of the U.T.S. It was found, however, that the springs became severely distorted when prestressed to this level and to maintain satisfactorily shaped springs, the solid stress level had to be reduced to approximately 61% of the tensile strength.

After coiling, the springs were subjected to various low temperature heat treatments according to the type of test to be carried out. Full details of the various treatments employed are given elsewhere in this report. All the springs were ground, and where appropriate, some springs were shot peened using CS330 shot to an Almen A arc rise of 0.5 mm. The shot peened springs were given a further L.T.H.T. at 200°C for $\frac{1}{2}$ hour. All the springs were fully prestressed as a final manufacturing operation before fatigue or relaxation testing.

4.2. Effect of L.T.H.T. on Fatigue Properties

To establish the optimum heat treatment temperature for springs intended for subsequent fatigue testing, a series of preliminary fatigue tests was carried out on unpeened springs which had received a variety of low temperature heat treatments. On the basis of the results, which are given in Fig. 4, a treatment of 400°C for $\frac{1}{2}$ hour was adopted for the test springs.

Similarly, to establish the best heat treatment to apply to the shot peened springs, the effects of a number of heat treatments over the range 200 to 450°C were investigated. On the basis of the results obtained as shown in Fig. 5, 200°C was chosen as the most suitable temperature for heat treating springs after shot peening.

4.3 Fatigue Tests on Springs

All the fatigue testing was carried out on forced motion spring fatigue testing machines. Each spring was load tested individually, to establish the required compressed length and machine stroke. Both unpeened and shot peened springs were tested at two initial stress levels and, from the data obtained, S/N curves and modified Goodman diagrams were constructed. (See Figs. 6 to 11).

Since the tensile strength of the two qualities of wire and their response to low temperature heat treatment were almost identical, only the U.H.T.3 material was made up into springs for the purpose of determining fatigue properties.

4.4. Stress-Relaxation Tests

Relaxation testing, also, was carried out only on springs manufactured from the U.H.T.3 wire. The springs were load tested and then compressed, by means of a nut and bolt assembly, to the required test stress, subjected to the selected elevated temperature for 72 hours and allowed to cool before being removed for further load testing at the original compressed length. From these two load measurements, the percentage loss in load was calculated.

The behaviour of the springs to five levels of stress, between 350 N/mm^2 and 790 N/mm^2, and at four temperatures, from 125°C to 200°C, was investigated. The results for unpeened springs are illustrated graphically in Fig. 12.

5. DISCUSSION OF RESULTS

5.1. Mechanical Properties of Wire

Firstly, a point must be made concerning the respective tensile strengths of the two qualities of wire in the as-received condition. Owing to supply problems, the two consignments were unfortunately received at different times and by the time the U.H.T.2 wire was received all the tensile and torsion testing on the U.H.T.3 material had been completed. It can be seen that the tensile strength of the U.H.T.3 wire, at 2146 N/mm^2, was slightly lower than that of the U.H.T.2 wire, at 2184 N/mm^2. This somewhat surprising result was inconvenient for the purposes of this investigation; it had been envisaged that there would be a discrete difference between the strengths of the two qualities which would be reflected in the results of subsequent tests. However, the tensile strength ranges quoted for U.H.T.2 and 3 materials do, in fact, overlap and such a situation may well arise in industry. When the anomaly was brought to the notice of the wire manufacturer, he was equally surprised at the similarity in strengths but gave an assurance that the U.H.T.3 material was produced from a higher quality base material and that processing schedules were designed to maintain, generally, a difference in minimum average strength of about 90 N/mm^2.

Like all patented cold drawn carbon steel wire, both qualities responded to the application of a low temperature heat treatment. The tensile strength of the U.H.T.2 wire increased by 5.7% and that of the U.H.T.3 wire by 8.3% when treated in the temperature range 175 to 225°C. A more spectacular improvement in the elastic properties is illustrated in Figs. 1 and 2 and Tables II and III: for both qualities, the 0.1% proof stress is some 66% of the as-drawn tensile strength, rising to 91% of the new tensile strength after heat treatment in the range 175 to 225°C. A similar pattern of behaviour was observed for the 0.2% and 0.5% proof stress values. In the latter case, however, it was not possible to record the values around the maxima of the curves (Figs. 1 and 2), for fear of damage to the extensometer.

The ductility of the wire, measured in the tensile test as the percentage elongation at fracture and in the torsion test as the number of twists to failure (Fig. 3), falls progressively with increased low temperature heat treatment temperatures, so that, when the tensile strength and proof stress are at a maximum, the ductility of the wire is at its lowest. Such a feature is unlikely to affect the production of helical compression springs, since the amount of ductility required in the wire for the purpose of pre-stressing is relatively small. However, the production of certain end hooks on extension springs, where plastic deformation is restricted to a very short length of wire, could present considerable problems, if U.H.T. wires were used which after coiling had, for example, received an L.T.H.T. of 200°C. In such a case, it would be better to form the hook end first and then heat treat but such an approach would have the disadvantage of lack of control over the relative positions of the two hook ends.

The torsional properties given in Tables IV and V also show the effect of a low temperature heat treatment: a considerable rise in the 0.1% proof stress and a less marked increase in the 0.2% proof stress figures. Although the tensile strengths of both wire qualities increased after a 200°C treatment, the maximum shear stress values were somewhat lower than those for the as-drawn wire. This drop in the maximum shear stress value can probably be attributed to the lack of torsional ductility and the opportunity for the wires to work harden during the torsion test.

5.2. Effect of L.T.H.T. on Springs

With helical compression springs, it is always desirable to carry out a low temperature heat treatment after coiling to relieve coiling stresses, to improve the elastic properties and to provide some measure of stability, particularly for springs operating at temperatures above ambient. Fig. 4 illustrates the fatigue behaviour of springs which have been heat treated at various temperatures after coiling. Testing was conducted at one stress level only, but it is clear that the endurance of unpeened springs can be improved by treatment at 400°C; above this temperature, however, there is evidence to suggest that the fatigue resistance begins to fall. Reference to the static properties of the wire shows that, with a 400°C treatment, the tensile and elastic properties are falling rapidly, the tensile strength being lower than the as-drawn value and the 0.1% proof stress figures little above the as-drawn value. This would suggest that two distinct treatments should be employed, depending on the ultimate service requirements of the spring: for static applications, a treatment around 200°C would give maximum elastic properties but for dynamic applications, a treatment at 400°C would appear to be more desirable.

With light springs, it is customary practice to apply some form of further heat treatment after shot peening and its influence on shot peened U.H.T.3 springs has been studied. Tests carried out at one stress level showed that temperatures up to 200°C had no effect on the fatigue resistance of the springs and even up to 300°C the reduction was only slight. Above this temperature, the fatigue resistance fell rapidly as the compressive stresses were relieved, as can be seen in Fig. 5.

From this work it was concluded that a heat treatment temperature of 200°C would be suitable for U.H.T.3 springs and this was used in preparing springs for the main part of the fatigue testing programme.

5.3. Fatigue Properties of Springs

S/N curves were produced for springs manufactured from the U.H.T.3 quality wire. These curves (Figs. 6, 7, 9 and 10) were used to draw two Goodman diagrams shown in Figs. 5, 8 and 11 for unpeened and shot peened springs respectively. It will be seen that at low initial stresses shot peening has more effect on fatigue resistance than at high initial stress levels. At the recommended maximum stress (i.e. 85% of the solid stress), from the experimental data available, there would appear to be no advantage in shot peening. Data from these curves are also summarised in Table VI and comparisons can be made with Table VII in which fatigue data are given for BS 1408 Range 3 springs. The information presented for the 4 mm diameter wire(2) is based on four separate consignments of wire, hence the quoted range in the fatigue limits.

It is clear that, in general terms, the fatigue properties of springs made from 3.16 mm U.H.T.3 wire are no better than those for springs manufactured from conventional BS 1408C and D, Range 3 qualities, which exhibit much lower tensile strengths. In the case of the 4 mm and 2.3 mm BS 1408R3 springs, the mean tensile strengths would be 1620 and 1775 N/mm^2 respectively, which on prestressing the springs to a solid stress of about 70% of the U.T.S. would produce a greater amount of plastic deformation and hence residual compressive stresses. The U.H.T.3 springs on the other hand, although much higher in tensile strength, at 2146 N/mm^2, were prestressed to a lower percentage of the U.T.S. (i.e. 61%) because of the problems of distortion. The springs in question were hand coiled and in consequence suffered from some variation in the form of one of the end coils which manifested itself on prestressing to 70% of the U.T.S. It seems likely that more regularly shaped springs could have been made by automatic coiling which would have allowed prestressing to the 70% level without excessive distortion.

Although it has been shown(3) that increasing the prestressing level can improve the fatigue resistance of springs, the increases are relatively small; it seems unlikely that, if unpeened U.H.T.3 springs had been prestressed to 70% of the U.T.S., there would have been any difference in the conclusion drawn. It is estimated that, at an initial stress of 100 N/mm^2, the maximum stress would have increased by only about 50 to 60 N/mm^2 which, when added to the figure quoted in Table VI would give an amended value of 720 N/mm^2. This value is similar to those given in Table VII for springs prestressed to 70% of their tensile strengths.

5.4. Stress Relaxation Properties

Fig. 12 shows the behaviour of unpeened U.H.T.3 springs when subjected to stress at elevated temperatures. The pattern of behaviour is quite normal and it will be seen that, with a 5% limiting amount of relaxation, the springs function quite satisfactorily at 125°C at all stress levels and at 150°C for stress levels up to 650 N/mm^2. Increasing the temperature above 150°C produced progressively more relaxation, so that at high stresses at 200°C an approximate loss in load of 12% is likely to occur.

Comparing these data with information previously obtained for patented cold drawn carbon steel springs(4, 5) of a similar wire diameter has shown that the U.H.T.3 springs possess somewhat superior resistance to relaxation. For example, at a stress of 700 N/mm^2 and a temperature of 150°C, U.H.T.3 springs exhibited 5.5% load loss, whereas BS 1408D and music wire springs relaxed by about 12%. It is suggested that this difference could well be a reflection of the higher tensile and elastic properties of the U.H.T.3 wire.

6. CONCLUSIONS

1. Both U.H.T.2 and 3 wire qualities responded to low temperature heat treatment with an increase in the elastic properties to a level considerably higher than can be obtained with conventional BS 1408 wires. The maximum improvement in properties occurred after treatment within the temperature range 175 to 225°C.

2. The ductility of wire treated within the range 175 to 225°C was reduced to a minimum.

3. Stress relieving the springs after coiling increased their fatigue resistance, the maximum improvement occurring after treatment at 400°C.

4. A further heat treatment at 200°C after shot peening did not affect adversely the fatigue resistance of

springs. Higher treatment temperatures, however, caused progressive reduction in fatigue resistance.

5. The fatigue properties of springs made from 3.15 mm diameter U.H.T.3 wire were similar to those of other top quality wire springs made from BS 1408C and D.

6. The stress relaxation resistance of springs made from U.H.T.3 wire was markedly better than that of BS 1408C and D quality springs.

7. REFERENCES

1. MEE J.W. "The fatigue properties of springs made from patented cold drawn wire to BS 1408C and D in three ranges of tensile strength". SRA Report No. 164.

2. BIRD G.C. "The fatigue properties of springs manufactured from patented cold drawn steel spring wire to BS 1408C and D". SRA Report No. 224.

3. BIRD G.C. "The effect of solid stress on the fatigue behaviour of springs manufactured from BS 1408C". SRA Report No. 219.

4. GRAVES G.B. "The stress-temperature relaxation properties of springs made from oil-tempered and patented hard drawn wires". SRA Report No. 115.

5. GRAVES G.B. "The stress-temperature and creep properties of some springs materials". SRA Report No. 143.

TABLE I CHEMICAL COMPOSITION OF U.H.T. WIRES

QUALITY	%C	%Si	%Mn	%S	%P	%Ni	%Cr	%Mo	%Cu	%Sn
U.H.T.2.	0.815	0.22	0.75	0.02	0.008	0.02	<0.02	< 0.005	0.01	<0.005
U.H.T.3.	0.795	0.21	0.73	0.013	0.011	0.03	0.02	0.005	0.03	0.005

TABLE II TENSILE PROPERTIES OF 3.15 mm dia U.H.T. 2 WIRE

L.T.H.T. °C	U.T.S. N/mm^2	PROOF STRESS N/mm^2			R. of A. %	Elongation %
		0.1%	0.2%	0.5%		
20	2184	1437	1703	2001	40.2	5.5
150	2318	2048	2203	-	-	4.5
175	2308	2094	2247	-	-	4
200	2305	2080	2222	-	47.8	2
225	2282	2100	2228	-	-	2.5
250	2251	2036	2176	2241	45.5	5
300	2170	1908	2010	2094	46.8	6
400	1892	1537	1632	1690	27.1	7

TABLE III TENSILE PROPERTIES OF 3.16 mm dia U.H.T. 3 WIRE

L.T.H.T. ^0C	U.T.S. N/mm^2	PROOF STRESS N/mm^2			R. of A. %	Elong-ation %
		0.1%	0.2%	0.5%		
20	2146	1387	1583	1874	47.2	6
100	2164	1590	1805	2045	47.2	5.25
150	2266	1969	2153	2240	35.9	4.5
175	2324	2077	2254	-	37.6	4.0
200	2326	2134	2242	-	41.8	2.75
225	2270	2103	2216	-	32.4	4.0
250	2229	2013	2153	2204	43.8	4.5
300	2093	1830	1938	2014	47.4	6.25
400	1795	1482	1520	1646	29.4	7.5

TABLE IV TORSIONAL PROPERTIES OF 3.15 mm dia U.H.T. 2 WIRE

CONDITION	MAX. SHEAR STRESS N/mm^2	PROOF STRESS N/mm^2			T.T.F. GL=100D
		0.1%	0.2%	0.5%	
AS REC'D	1624	776	914	-	31
	1539	788	914	-	25
MEAN	1581	782	914	-	28
L.T.H.T. 200^{0}C ½h	1421	1080	1190	-	8
	1347	1038	1190	-	7
MEAN	1384	1059	1190	-	7.5

TABLE V TORSIONAL PROPERTIES OF 3.16 mm dia U.H.T. 3 WIRE

CONDITION	MAX. SHEAR STRESS N/mm^2	PROOF STRESS N/mm^2			T.T.F. GL=100D
		0.1%	0.2%	0.5%	
AS REC'D	1750 1653	736 722	845 886	995 -	32 30
MEAN	1702	729	865	995	31
L.T.H.T. 200^{0}C ½h	1533 1457	1136 1022	1226 1158	-	8 4
MEAN	1495	1079	1192	-	6

TABLE VI FATIGUE DATA FOR U.H.T. 3 SPRINGS

3.16 mm dia WIRE

Initial Stress (N/mm^2)	Fatigue limit at 10^7 cycles (N/mm^2)	
	Unpeened	Shot peened
zero	580	820
88	650	850
100	660	860
300	810	930
438	910	980

TABLE VII FATIGUE DATA FOR SOME BS 1408 WIRE SPRINGS

Ref	Quality	Size (mm)	Initial Stress N/mm^2	Fatigue limit at 10^7 cycles (N/mm^2)	
				Unpeened	Shot peened
2	BS 1408C R3	4	100 300	640-760 800-900	800-880 960-980
2	BS 1408D R3	4	100 300	720-780 840-880	800-900 960-1020
3	BS 1408C R3	2.3	100 300	780 910	900 1010

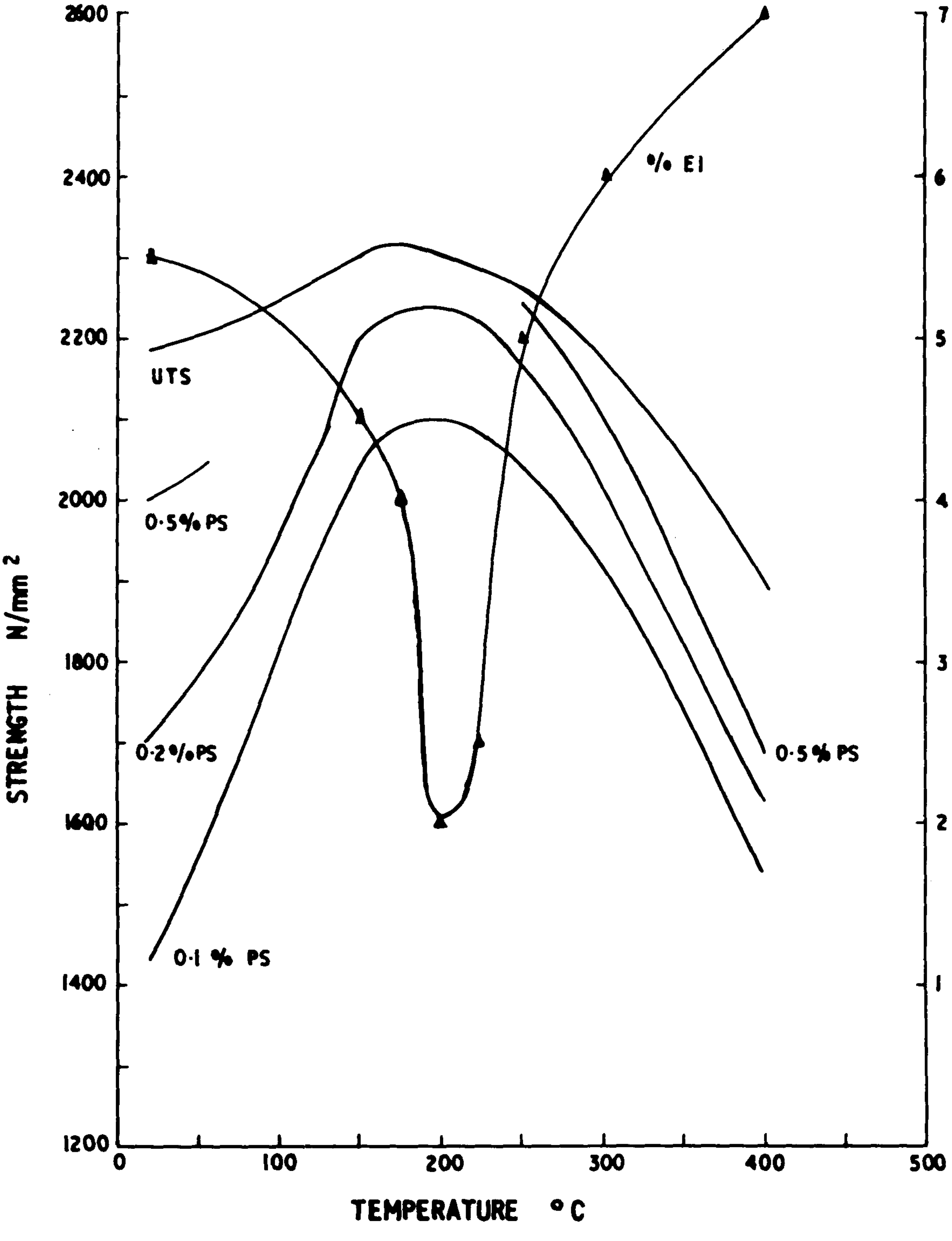

FIG. I EFFECT OF L.T.H.T. ON THE PROPERTIES OF 3·15 mm dia. UHT 2 WIRE.

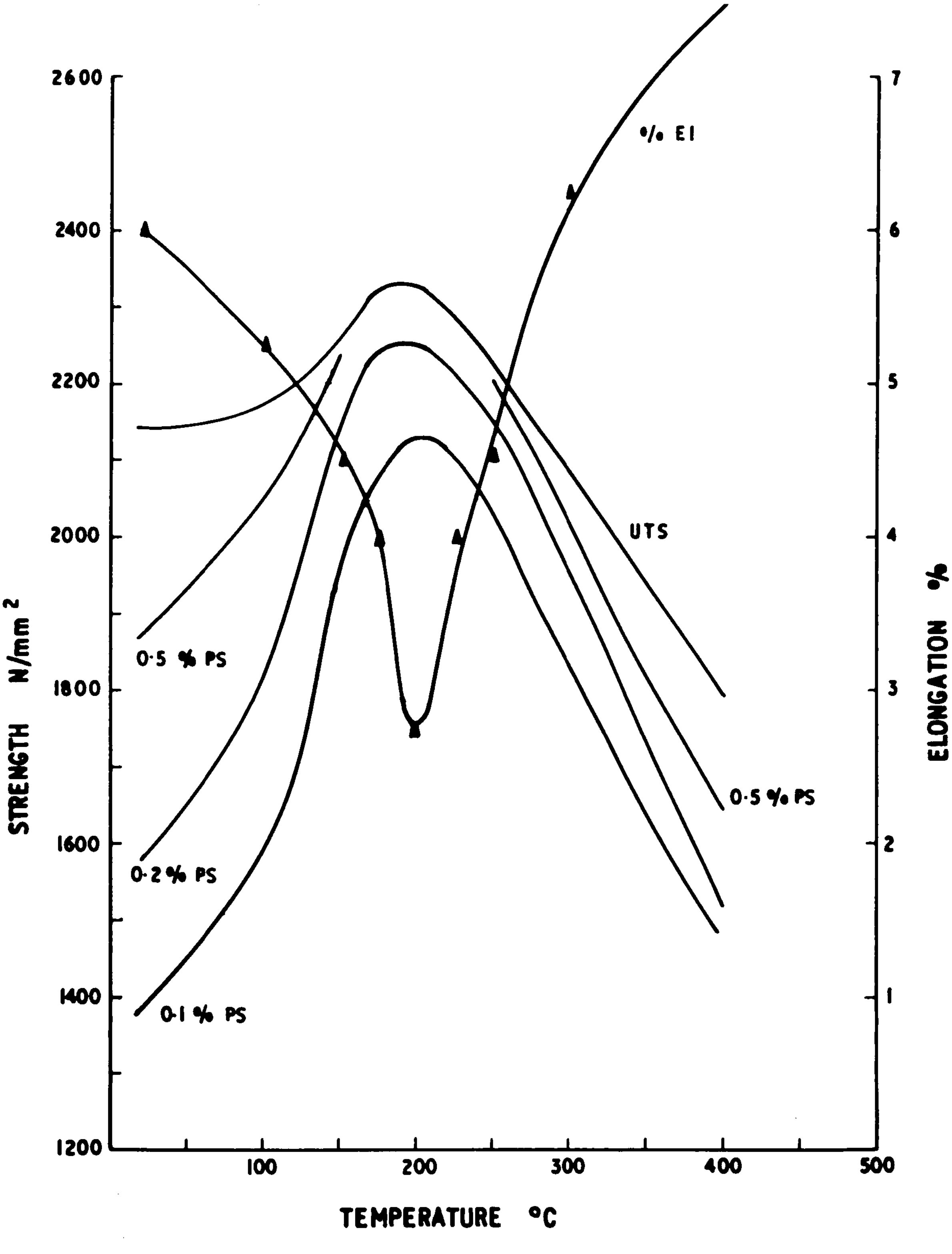

FIG. 2 EFFECT OF L.T.H.T. ON THE PROPERTIES OF 3·16 mm dia. UHT 3 WIRE.

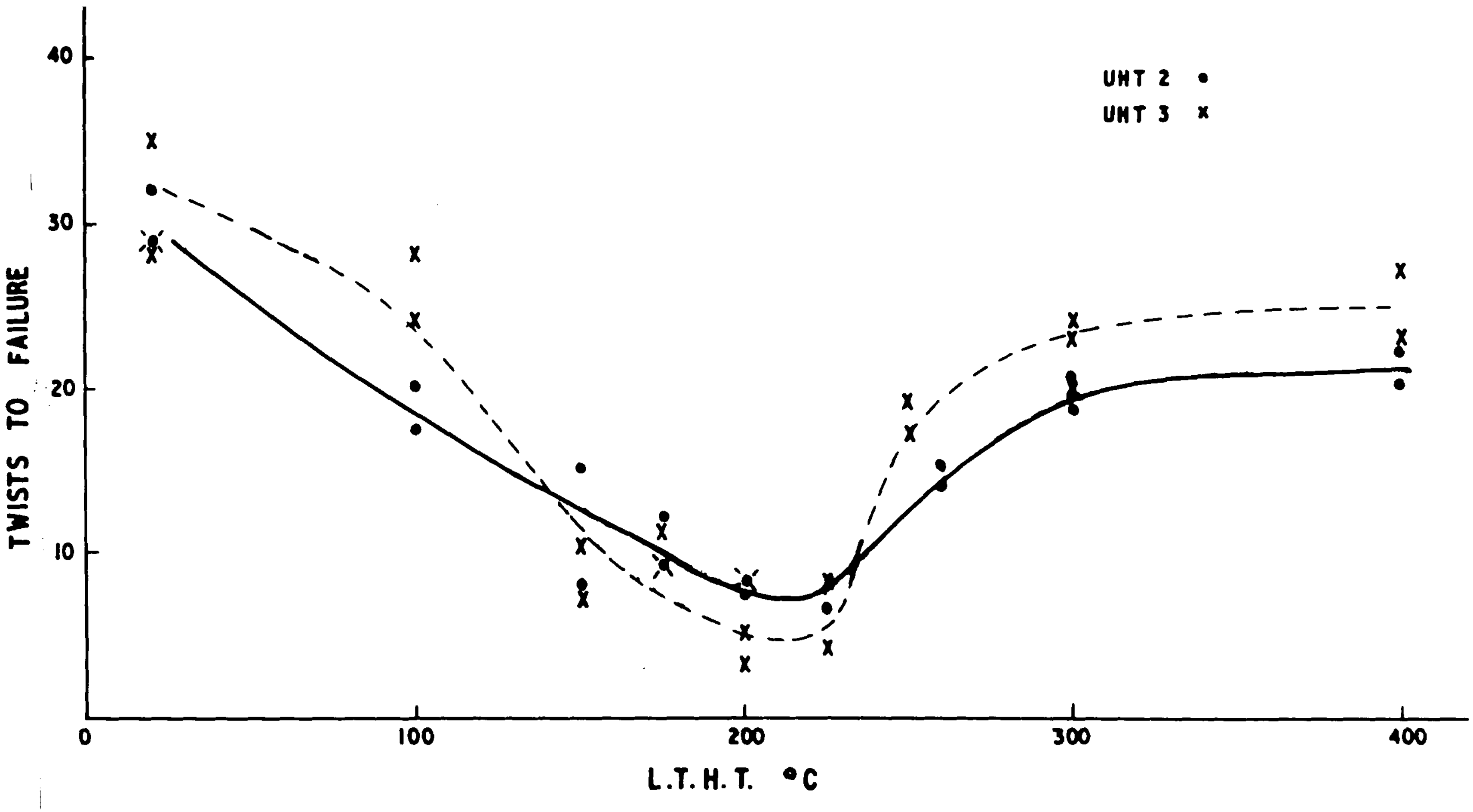

FIG. 3 EFFECT OF L.T.H.T. ON TORSIONAL DUCTILITY OF UHT WIRES. (G.L. 100d)

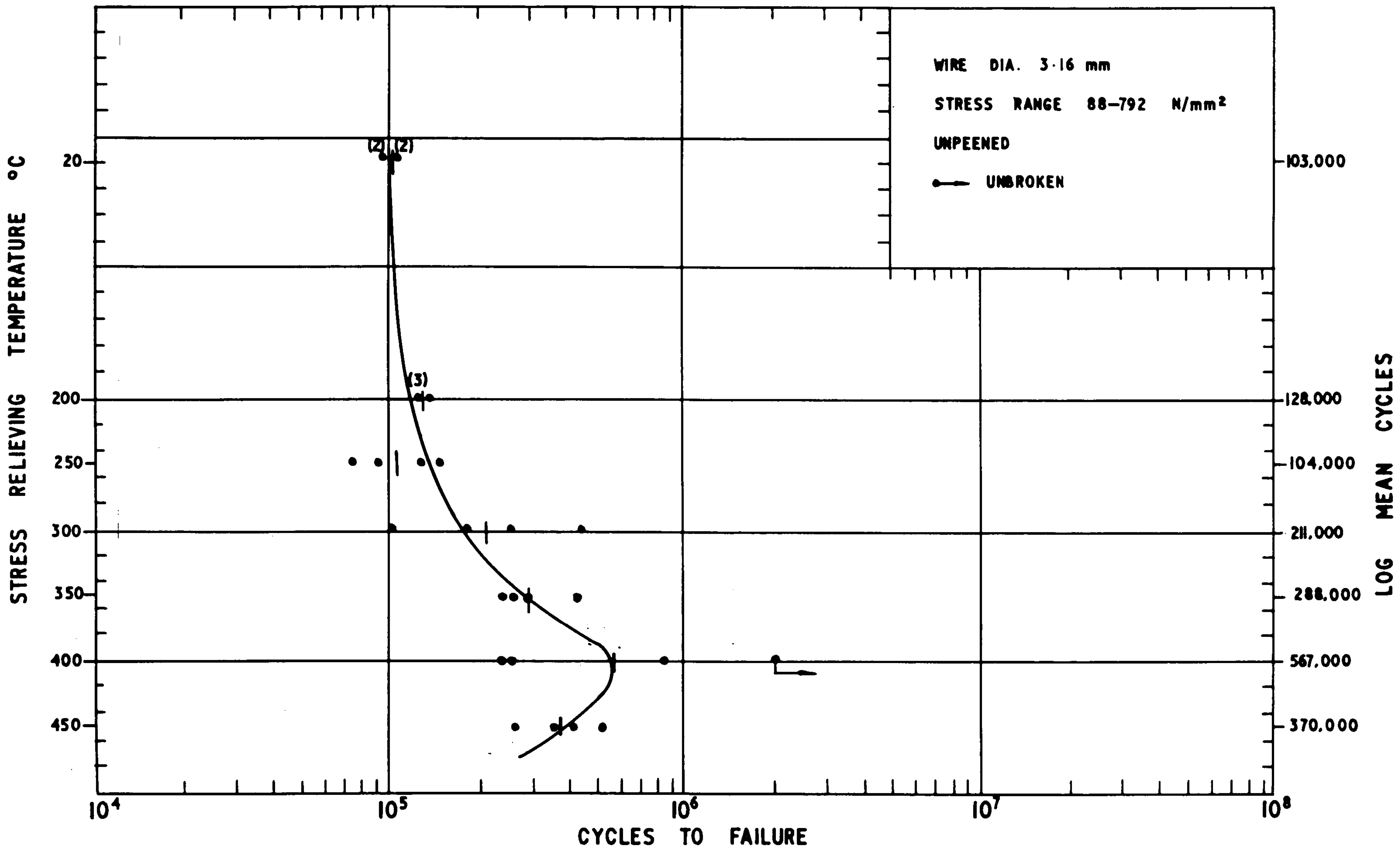

FIG. 4 EFFECT OF L.T.H.T. ON FATIGUE RESISTANCE OF UNPEENED UHT 3 SPRINGS.

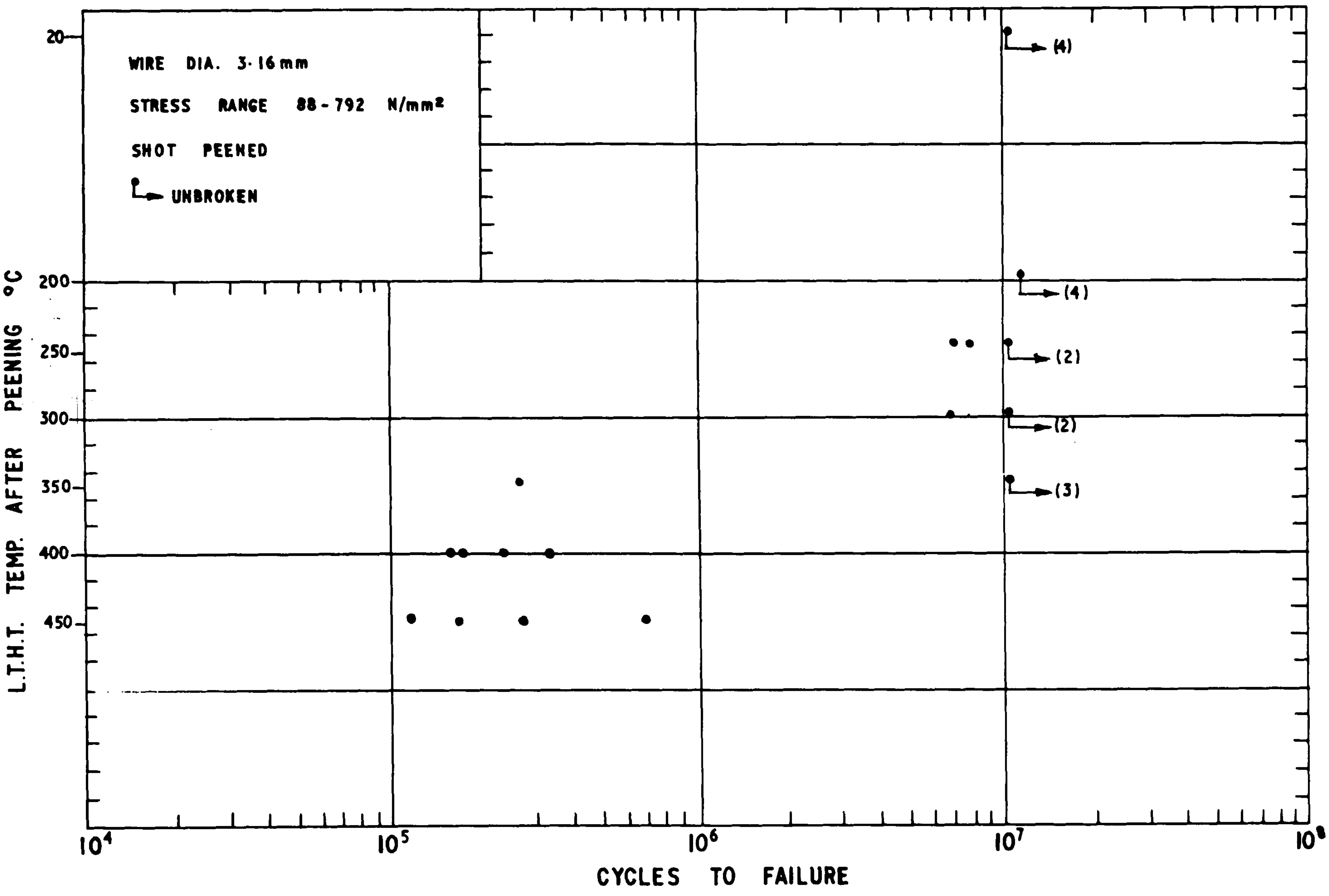

FIG. 5 EFFECT OF L.T.H.T. ON THE FATIGUE PROPERTIES OF SHOT PEENED UHT 3 SPRINGS.

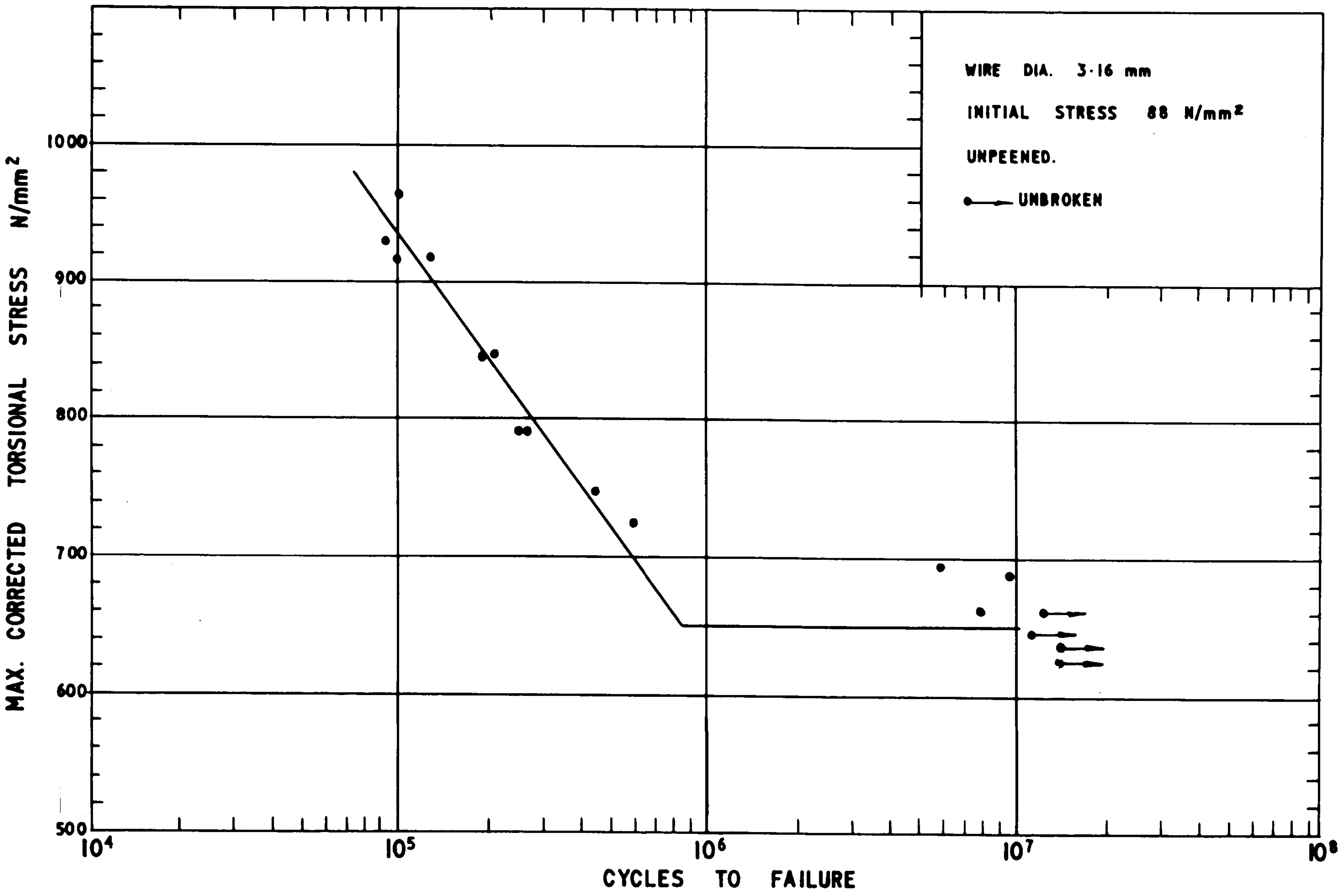

FIG. 6 S/N CURVE FOR UNPEENED UHT 3 SPRINGS, INITIAL STRESS 88 N/mm²

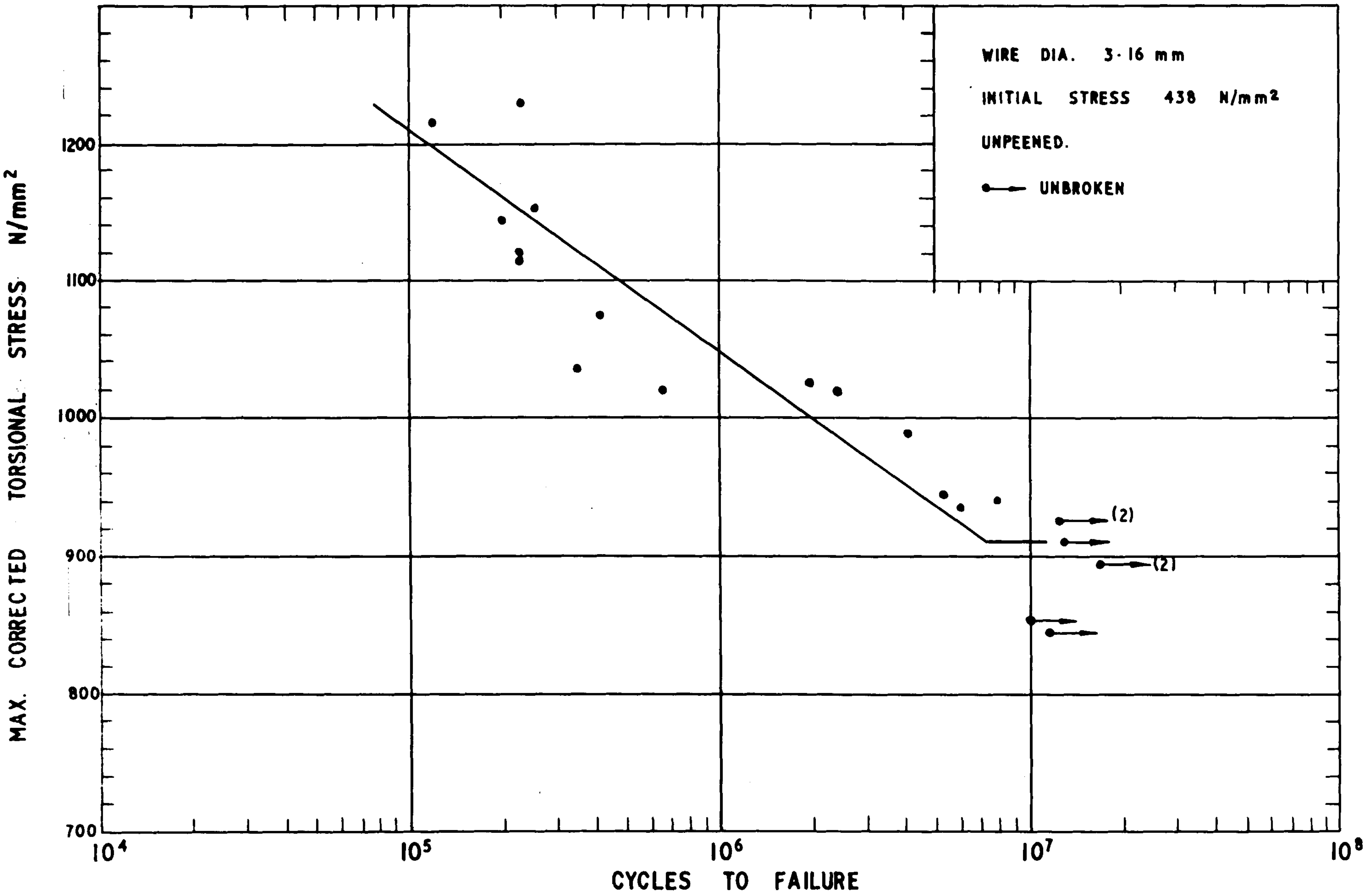

FIG. 7 S/N CURVE FOR UNPEENED UHT 3 SPRINGS, INITIAL STRESS 438 N/mm²

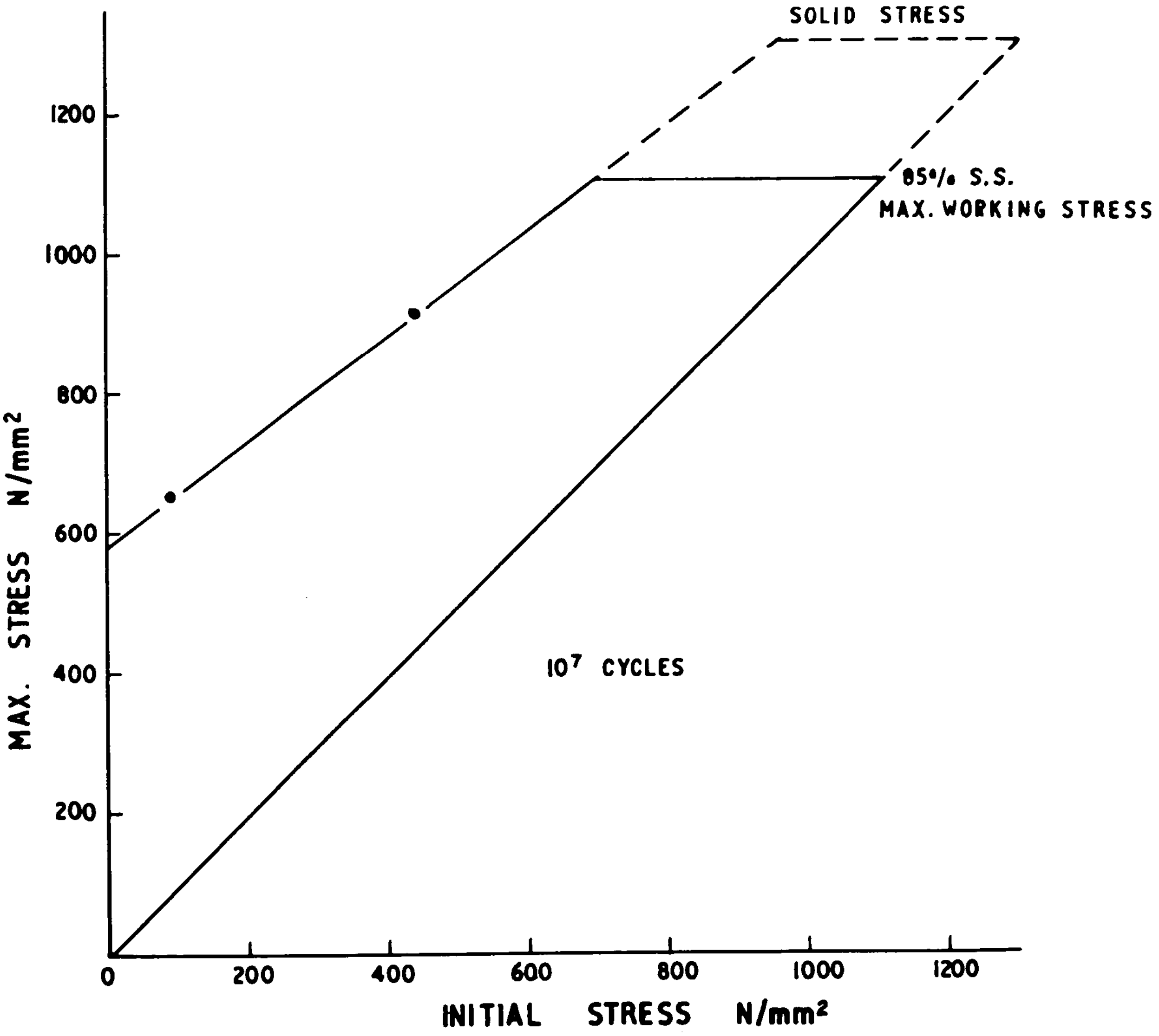

FIG. 8 MODIFIED GOODMAN DIAGRAM FOR 3·16 mm. UHT 3 WIRE SPRINGS. (UNPEENED)

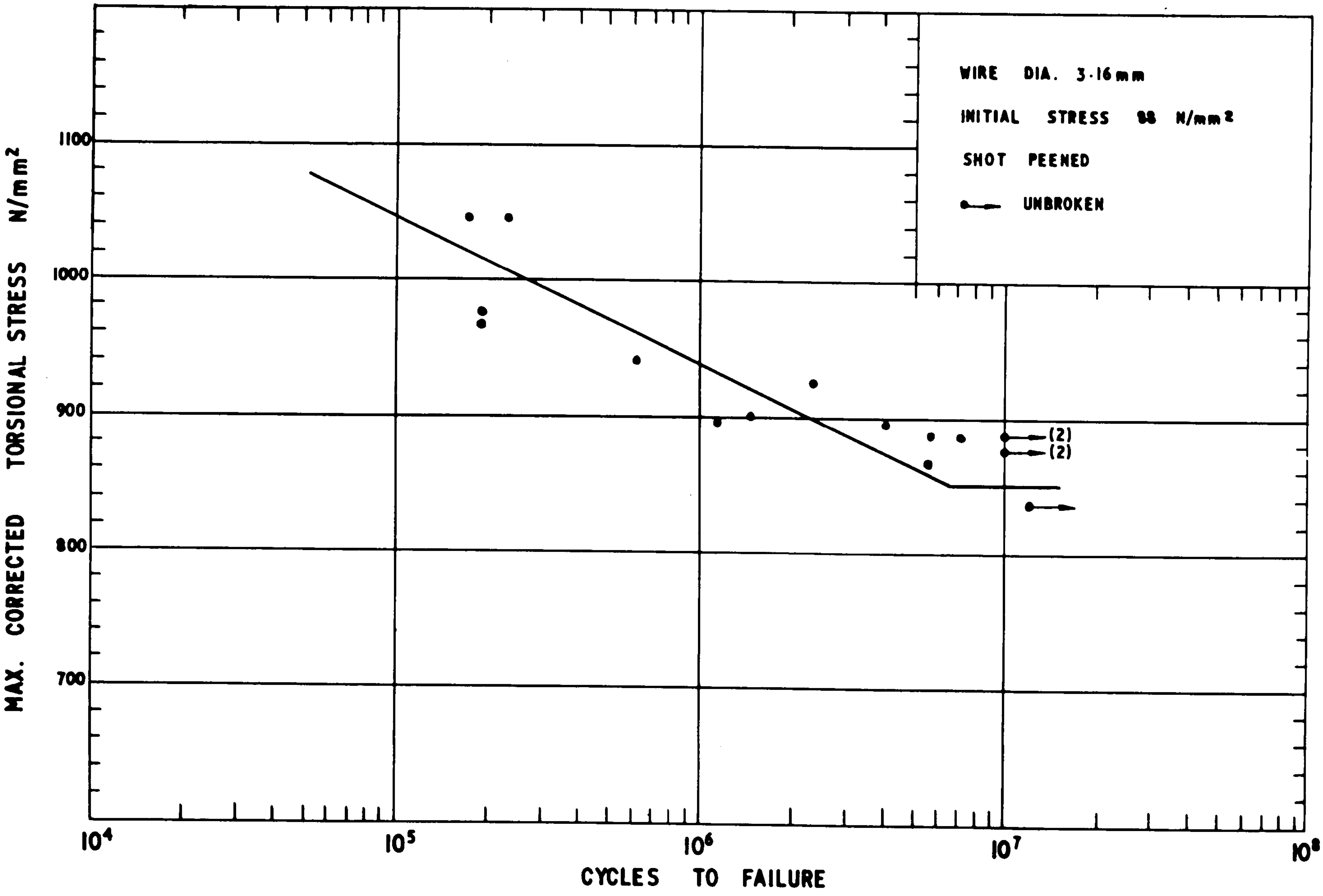

FIG. 9 S/N CURVE FOR SHOT PEENED UHT 3 SPRINGS, INITIAL STRESS 88 N/mm²

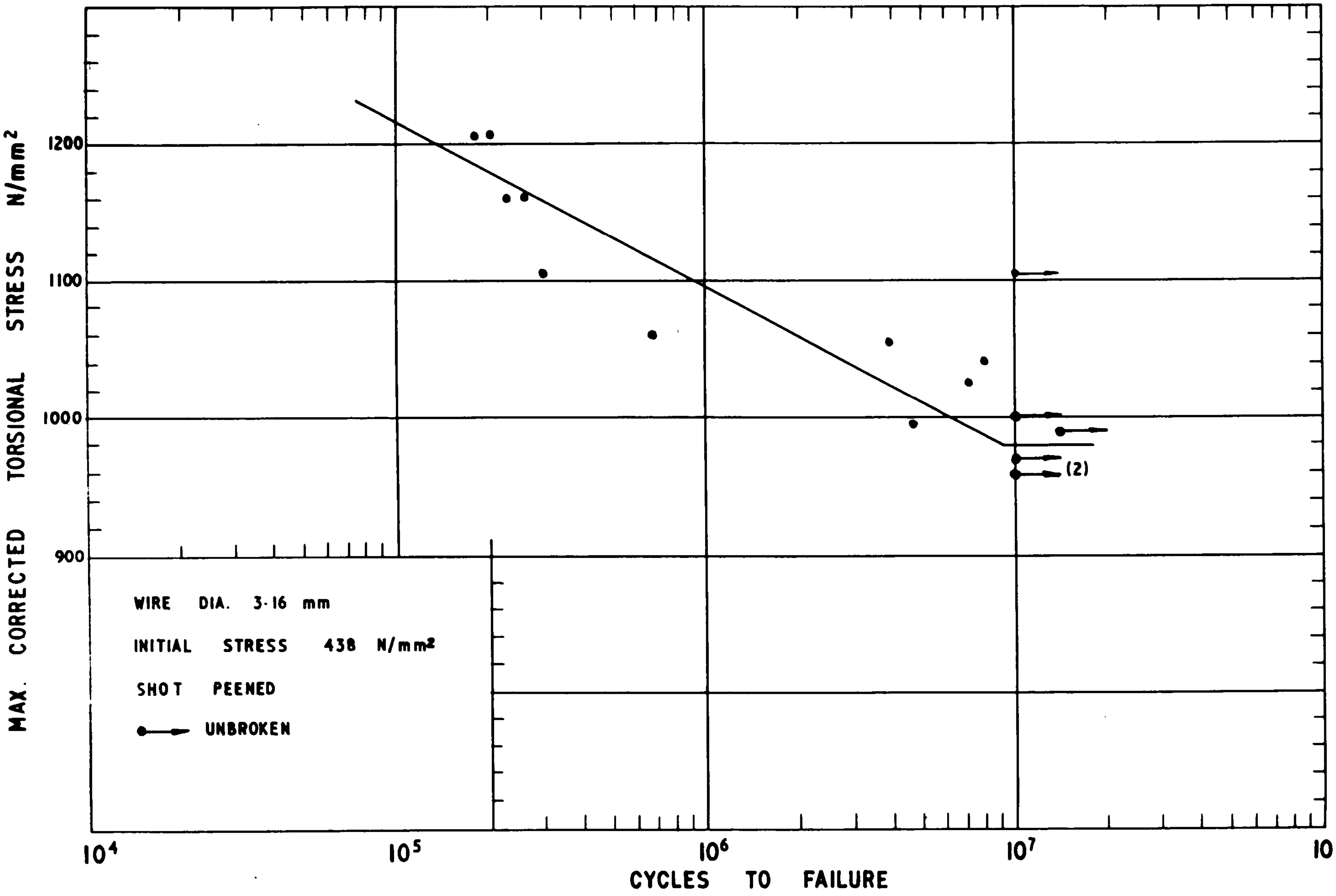

FIG. 10 S/N CURVE FOR SHOT PEENED UHT 3 SPRINGS, INITIAL STRESS 438 N/mm^2

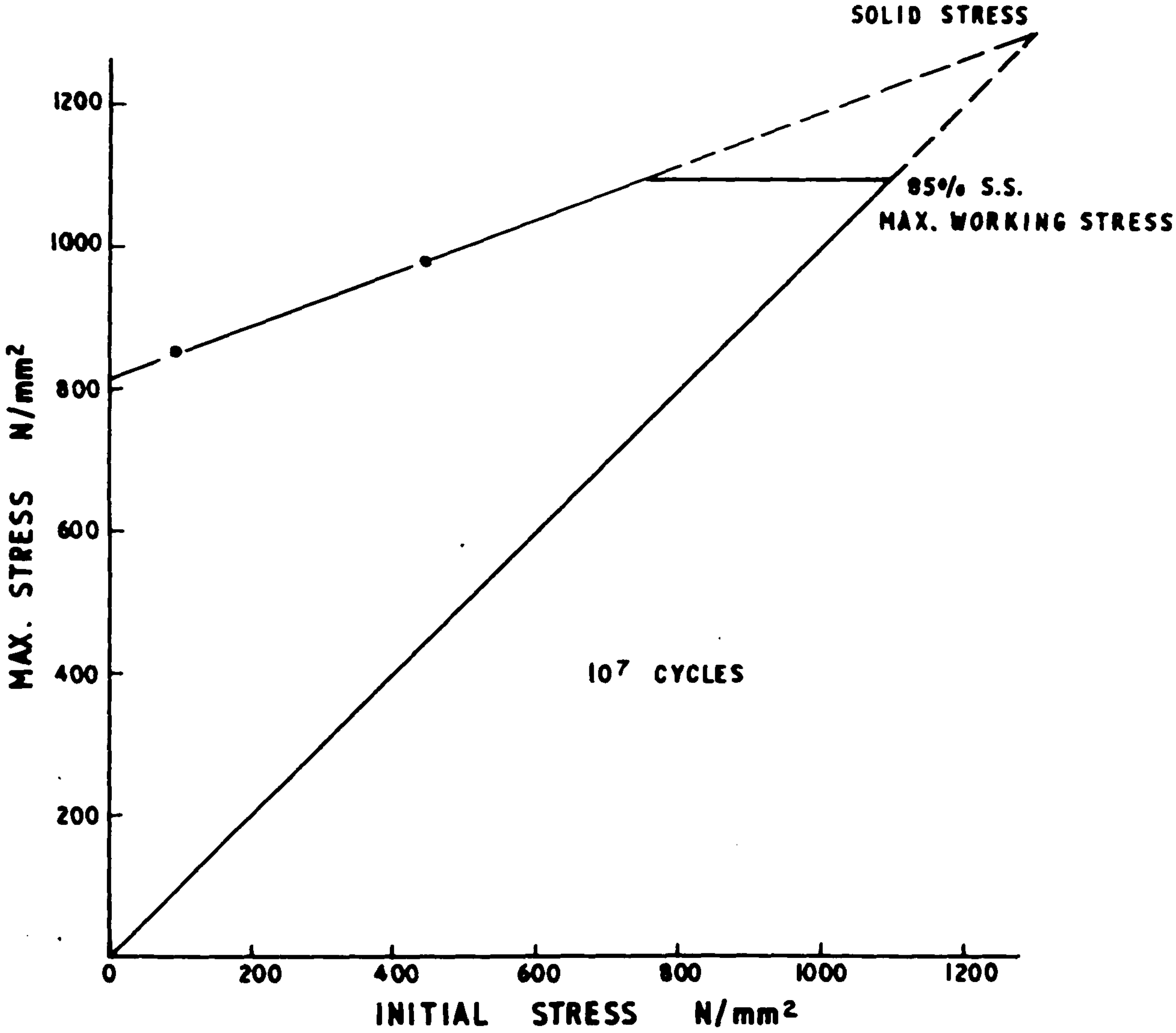

FIG. 11 MODIFIED GOODMAN DIAGRAM FOR 3·16 mm UHT 3 WIRE SPRINGS. (SHOT PEENED.)

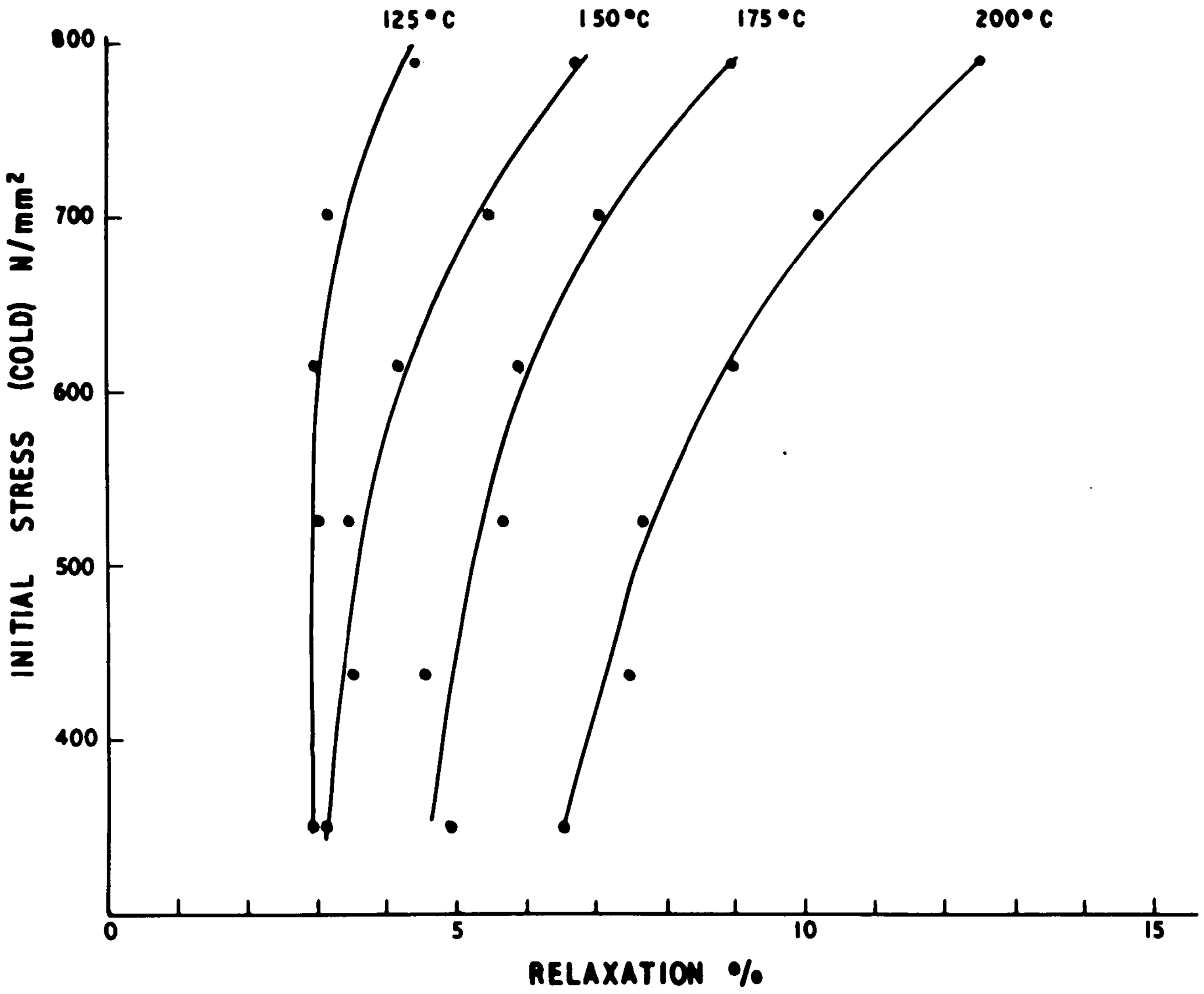

FIG. 12 STRESS TEMPERATURE RELAXATION PROPERTIES OF UNPEENED UHT 3 SPRINGS.