THE SPRING RESEARCH ASSOCIATION

THE FATIGUE AND RELAXATION PROPERTIES OF HELICAL COMPRESSION SPRINGS MADE FROM PHOSPHOR-BRONZE WIRE

by

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SUMMARY

Fatigue tests have been carried out on helical compression springs made from 1.22 mm diameter phosphor-bronze wire in the extra-hard condition. Testing was performed at three initial stress levels, enabling a modified Goodman diagram to be constructed for lives of 10^5, 10^6 and 10^7 cycles.

Elevated temperature tests of up to 72 hours' duration have also been carried out at each of five initial stress levels. It has thus been possible to relate initial stress and % relaxation over this time period for a range of temperatures between 50°C and 125°C. In addition some limited testing was carried out to examine the effect of increased time, up to 250 hours, on the relaxation occurring at 75°C for the five test stresses.

Results suggest that relaxation increases rapidly above 100°C but even below this temperature a significant amount of relaxation occurs particularly at the higher stress levels. For any working stress, if relaxation is to remain below 7% the temperature must not exceed 75°C.

Room temperature stress relaxation tests were also carried out using the same five initial stresses. Results indicate that over a four month period relaxation does not exceed 2% even at the highest test stress.

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1. INTRODUCTION

Copper-base alloys are used as spring materials because of their high electrical conductivity and good corrosion resistance. Of the three copper alloys used for springs, phosphor-bronze is the most common, being less expensive than copper-beryllium and more corrosion resistant than spring-brass. Copper-beryllium is a precipitation hardening alloy while phosphor-bronze and spring-brass can only be strengthened by cold work. Phosphor-bronze wire can be obtained commercially in two compositions, containing 5 and 7% tin respectively. They are supplied in a range of tensile strengths according to the degree of cold work which they have received.

Only a small amount of data concerning the fatigue and relaxation properties of compression springs made from phosphor-bronze wire is to be found in the literature. In the one case where quantitive results are quoted, details of spring design and pre-treatment are omitted[1]. In the present work, a more comprehensive study has been undertaken in order to produce significant results which are of real practical value. Fatigue tests have been carried out on compression springs made 1.22 mm diameter, phosphor-bronze spring wire, using each of three initial stresses.

On the basis of the results obtained, modified Goodman diagrams have been constructed for lives of 10^5, 10^6 and 10^7 cycles. Short term stress relaxation tests have also been carried out, using four test temperatures and five stresses. Long term room temperature stress relaxation tests have been performed at each of the five tests stresses.

2. MATERIAL

2.1 Composition

Phosphor-bronze wire having a diameter of 1.22 mm and manufactured in accordance with BS 2873:1969 was obtained in the extra-hard condition. The chemical composition, as shown in Table I, conforms to the designation PB 102 within the above specification.

2.2 Spring Design and Manufacture

All springs were manufactured according to the design details given in Table II. The solid stress quoted is calculated from the standard formula:

$$q = \frac{8PDK}{\pi d^3}$$

where:
- q = Shear stress
- p = Load
- D = Mean diameter
- K = Sopwith correction factor
- d = Wire diameter

Approximately 250 springs were coiled on a Torrington 115A coiling machine and were subsequently stress relieved at 200°C for half an hour. When springs of this type are stress relieved after coiling the treatment given here is typical of that which is used in industry. The springs were then end ground and prestressed to solid until no further decrease in length occurred.

3. EXPERIMENTAL PROCEDURE

3.1 Mechanical Testing

In each case, samples of wire in both the as-drawn and the low-temperature heat-treated conditions were tested. The results were obtained by taking the average of three sets of test results.

3.1.1 Tensile Testing

The tests were carried out on a vertical Amsler multi-range tensile testing machine, equipped with an automatic stress-strain recorder. The latter was used in conjunction with an extensometer having a 250 mm gauge length.

3.1.2 Torsion Testing

Torsion testing was carried out on a vertical Amsler torsion testing machine with a maximum capacity of 5.6 Nm. The gauge length was one hundred times the wire diameter, that is, 122 mm. Torsional stresses were calculated using the formula:-

$$q = \frac{16T}{\pi d^3}$$

where q = Shear stress
T = Torque
d = Diameter

3.2 Fatigue Testing

Fatigue tests were carried out using initial stresses of 100, 150 and 200 N/mm^2. Each spring was load tested to determine the deflections necessary to give the initial stress and the maximum stroke was calculated. A forced-motion, multiple-station fatigue testing machine, operating at 1500 rpm, was employed.

3.3 Stress Relaxation Testing

The five stresses chosen for this part of the work, which were used for both the short term and the long term tests, were 100, 200, 300, 400 and 500 N/mm^2. Springs were load tested individually in order to determine the compressed length necessary to achieve the particular test stress required. Hence the stress values given above refer to the actual stress on the springs at room temperature. Nut and bolt assemblies were used to hold the springs at the pre-determined compressed lengths. For each combination of stress and temperature, tests were carried out in triplicate.

After the required time under the test conditions, each spring was unbolted and load tested to its original compressed length. The percentage loss in load was taken as a measure of the relaxation which had occurred in the spring during the test.

3.3.1 Short Term Tests at Elevated Temperatures

These tests were of seventy-two hours' duration, which from previous tests on carbon steel and Cu-Be wire springs had been shown to produce the majority of relaxation likely to occur with time at elevated temperatures. The test temperatures selected were 50, 75, 100 and 125°C, these being chosen to include the various maximum working temperatures for phosphor-bronze springs recommended in the literature.

3.3.2 Longer Term Tests at Elevated Temperature

For reasons to be outlined in section 5.2.1, some limited tests were carried out at 75°C using springs stressed to all five levels, data being obtained at regular intervals up to a duration of 250h.

3.3.3 Long Term Tests at Room Temperature

Test springs were bolted down to the appropriate compressed lengths for each of the five test stresses, and stored carefully at room temperature for approximately four months. At regular intervals within this period, the percentage relaxation was determined as previously described.

4. RESULTS

The chemical analysis of the phosphor-bronze wire used in this investigation is given in Table I and the spring design is detailed in Table II. The results of the static mechanical tests are shown in Tables III and IV. Torsional fatigue curves for the three initial stress levels are given in Figs. 1, 2 and 3. Fig. 4 is a modified Goodman diagram showing results at 10^5, 10^6 and 10^7 cycles endurance. In Figs. 1-4 inclusive, a continuous line represents the

"best fit" line through the experimental points, constructed by the method of least squares. In each case, the dashed line is the 95% confidence limit line.

The results of the 72-hour elevated temperature stress relaxation tests are summarised in Fig. 5 and tests carried out at 75°C for durations up to 250h shown in Fig. 6.

The results of the long term room temperature stress relaxation tests are shown in Table V.

5. DISCUSSION

5.1 Fatigue Tests

From the Goodman diagram in Fig. 4 it can be seen that the pattern of fatigue test results is similar to that which has been reported many times for ferrous spring materials. The fatigue properties of springs made from phosphor-bronze wire can best be compared with those of springs made from hard drawn carbon steel wire by examining the relative fatigue ratios. In this case, the latter is defined as the ratio of the fatigue stress range (10^7 cycles) to the tensile strength. At zero initial stress, the fatigue ratio has a value of 0.31 for the phosphor-bronze springs. Using data presented in a previous report[5], it can be shown by calculation that, for unpeened springs made from BS 1408C material, the fatigue ratio at zero initial stress varies between 0.36 and 0.41 depending on the tensile range. For springs manufactured from BS 1408D material, the range of fatigue ratio is 0.40 to 0.45. Hence, at zero initial stress the fatigue performance of phosphor-bronze springs is inherently worse than that of springs made from either ground or unground hard drawn carbon steel wire.

At an initial stress of 200 N/mm^2, the fatigue ratio for phosphor-bronze springs falls to 0.28, while for the carbon steel springs of both qualities the value is between 0.33 and 0.44. Thus, it may be concluded that, as the initial

stress increases, the maximum allowable shear stress increases less rapidly for phosphor-bronze springs than for springs made from hard drawn carbon steel.

5.2 Relaxation Tests

5.2.1 Elevated Temperature Data

The data given in Fig. 5 provides a correlation between initial stress and the amount of relaxation obtained over a period of 72 hours at a particular elevated temperature. It can be seen that, for an initial stress of 100 N/mm^2, heating to 50°C for 72 hours results in an increase in the load bearing capacity of the spring, owing to recovery from the prestressing operation. When the initial stress is raised to 200 N/mm^2 at the same temperature, the effects of recovery and relaxation balance exactly and there is no alteration in the load bearing capacity of the spring. At higher test temperatures, however, the relaxation effect predominates at all stress levels.

Several references to a 'maximum operating temperature' for phosphor-bronze springs can be found in the literature. In most cases, this temperature is defined in terms of allowable relaxation over a particular period of time at a particular working stress. The level of this allowable relaxation varies from author to author, presumably depending on the intended application of the test springs employed. For example, a level of not more than 6% relaxation at a test stress of 300-400 N/mm^2 over a 168-hour period has been quoted[2], as has less than 5% relaxation in 48 hours[3]. In both these instances, details of the spring design are not given, but the recommended maximum operating temperature is the same, that is 110°C.

The results of the present investigation are of real practical value in that they show the spring user the actual % relaxation that can be expected over a 72-hour period for a variety of working stresses and temperatures.

Knowing his working stress and temperature, the user can then decide whether the predicted amount of relaxation is permissible for the application in question.

Some relaxation data for copper-beryllium springs similar in design to those used in the present work are to be found in a previous SRA report[4]. Comparison of the results reveals that copper-beryllium has a slightly better resistance to relaxation than phosphor-bronze. One of the more important findings the previous work was that at a test temperature of 100°C relaxation increased with time up to 72 hours' exposure but at longer exposures no significant increase in relaxation occurred. It may seem reasonable to apply this conclusion to the data presented here for phosphor-bronze springs but it is arguable whether, at temperatures below 100°C, any significant additional relaxation occurs above 72 hours' test duration. Accordingly, relaxation tests were carried out on a small batch of springs in order to investigate the effect of increased time on the % relaxation occurring at 75°C. All five test stresses were used and the results are shown in Fig. 6.

It can be seen from this graph that at the two highest test stresses the amount of relaxation occurring at 75°C does not increase appreciably after 144 hours' exposure. In each case the additional relaxation occurring after the initial 72-hour period is of the order of 2%. For the lower stresses, the plateaux of the curves have not been established but it seems improbable that the maximum % relaxation at this temperature will exceed 5% at any of the three lower stresses. Hence it may be concluded tentatively that for stresses up to 500 N/mm^2 the amount of relaxation at 75°C is unlikely to exceed 7%. It should be remembered that this conclusion is based on results obtained with only a small number of springs and a more comprehensive investigation is obviously necessary. However, it has been adequately demonstrated that at 75°C relaxation is not confined to an initial 72-hour period, as was previously thought.

5.2.2 Room Temperature Data

From Table V it can be seen that over the test period significant relaxation only occurs at stresses of 300 N/mm^2 and above. At stresses below this level, the small amounts of relaxation recorded are well within the range of experimental error and are not therefore regarded as significant. The important feature of these room temperature data is that over a four-month period the relaxation at a stress of 500 N/mm^2 was 1.7%. Although the stress level is high, it is still within the recommended working stress range for springs made from phosphor-bronze wire. Although the amount of relaxation is small by comparison with the elevated temperature results, it may nevertheless be of practical significance in certain applications. The tests are being continued and it may be that over longer periods significant relaxation will occur at the lower test stresses. Any further results will be made the subject of a future report.

6. CONCLUSIONS

1. A modified Goodman diagram has been constructed which enables the working stress range for helical compression springs made from phosphor-bronze wire to be determined for lives of 10^5, 10^6 and 10^7 cycles.

2. Relaxation data have been produced for a 72-hour relaxation time, from which it is possible to predict the relaxation occurring in a spring, as a function of the applied stress and the ambient temperature.

3. If the relaxation is to remain below 7% at any working stress, the temperature must not exceed 75°C.

4. Relaxation of approximately 2% can occur at room temperature over a four-month period at a stress of 500 N/mm^2.

7. SUGGESTIONS FOR FURTHER WORK

7.1 Fatigue

It has been suggested that the fatigue performance of phosphor-bronze compression springs may be significantly improved at all initial stress levels if the springs are shot peened before prestressing. Peening with relatively small diameter shot could induce beneficial residual compressive stresses in the surface of the springs, while at the same time keeping distortion to a minimum.

7.2 Relaxation

As previously mentioned, it is important that the effect of increased times, above 72 hours, on the relaxation properties of phosphor-bronze springs at elevated temperatures be investigated thoroughly.

Room temperature stress relaxation tests are being continued at all five stress levels.

8. REFERENCES

1. CARLSON H.C.R. "Allowable Working Stresses for Springs". Prod. Eng., March 1954.

2. International Nickel Co. Ltd., "Spring Materials for High Temperature Service". Prod. Eng., Aug. 1956.

3. CARLSON H.C.R. "Selection and Application of Spring Materials". Mech. Eng., April 1956.

4. GRAVES G.B. "Stress Temperature Relaxation and Creep Properties of Some Spring Materials". SRA Report 143.

5. MEE J.W. "The Fatigue Properties of Springs made from Patented Cold Drawn Wire to BS 1408C and BS 1408D in Three Ranges of Tensile Strength". SRA Report 164.

TABLE I CHEMICAL COMPOSITION

	% Cu	% Sn	% P	% Pb
Nominal	Rem.	4.5 - 6.0	0.02 - 0.40	0.2
Actual	94.72	4.89	0.17	-

TABLE II SPRING DESIGN

Wire Diameter (mm)	1.22
Mean Coil Diameter (mm)	9.75
Total No. of Coils	9
No. of Active Coils	7
Free Length (After End Grinding And Prestressing) (mm)	31.24
Solid Stress (After End Grinding And Prestressing) (N/mm^2)	600

TABLE III TENSILE PROPERTIES OF PHOSPHOR-BRONZE WIRE

Condition	Tensile Strength		0.1% P.S.		0.2% P.S.		L of P		ELONG.
	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	%
As Drawn	57.0 880 N/mm²	881	48.9	756	53.7	830	34.1	527	3.1
After L.T.H.T.	55.8	862	51.5	789	54.2	837	37.0	572	2.4

TABLE IV TORSIONAL PROPERTIES OF PHOSPHOR-BRONZE WIRE

Condition	Max. Shear Stress		0.1% P.S.		0.2% P.S.		L of P	
	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2	tonf/in^2	N/mm^2
As Drawn	44.4	686	36.5	564	40.0	618	20.6	318
After L.T.H.T.	43.5	672	35.3	545	37.8	584	21.5	332

TABLE V RELAXATION AT ROOM TEMPERATURE

Time hrs. \ Stress N/mm^2	100	200	300	400	500
72	0	0	0	0.6	0
240	0	0	0	0.4	0
792	0	0	0	0.3	0.8
1584	0	0	0	0.3	0.4
2856	0.5	0	0.6	0.6	1.7

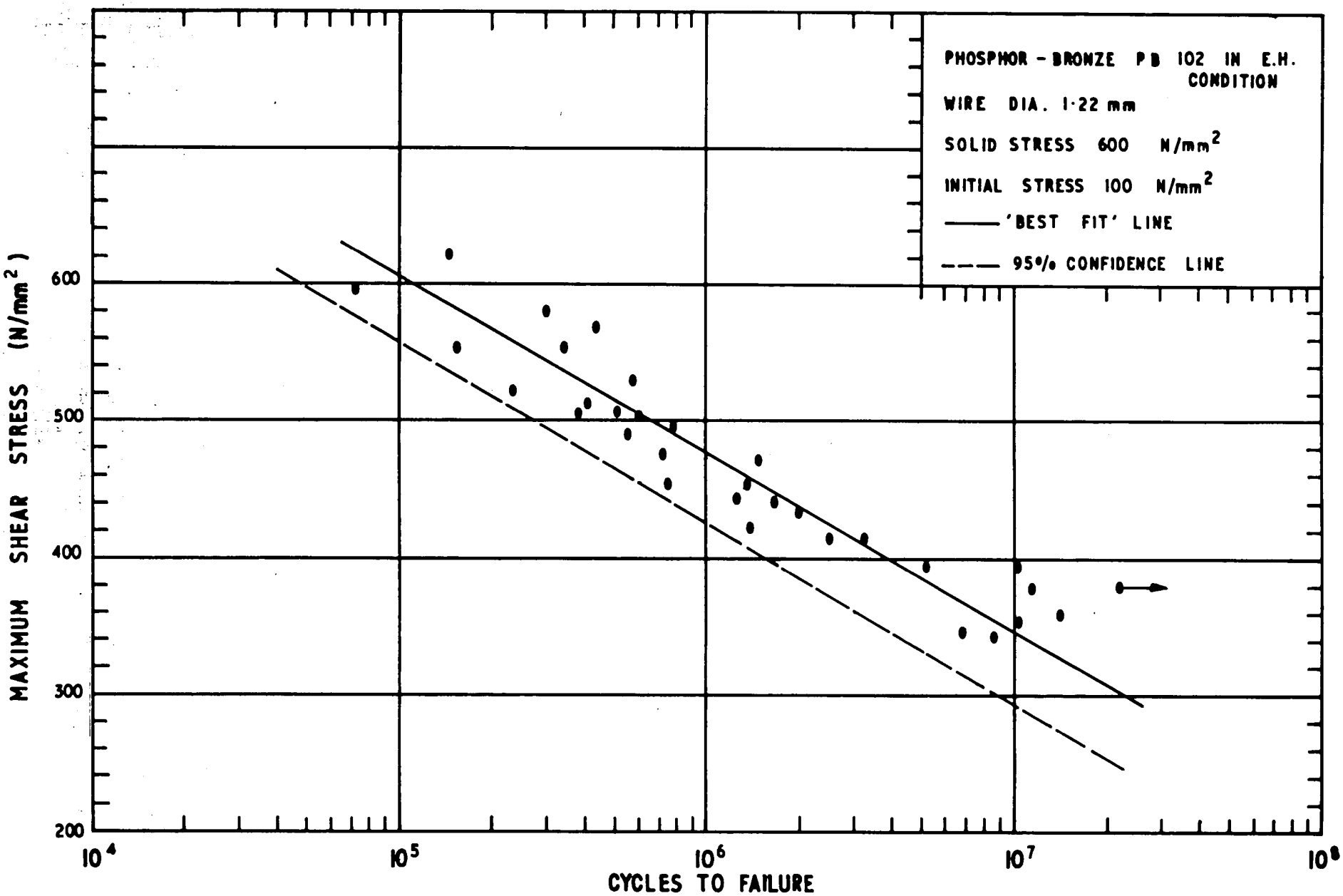

FIG. 1. TORSIONAL S/N CURVE FOR PHOSPHOR - BRONZE SPRINGS INITIAL STRESS 100 N/mm²

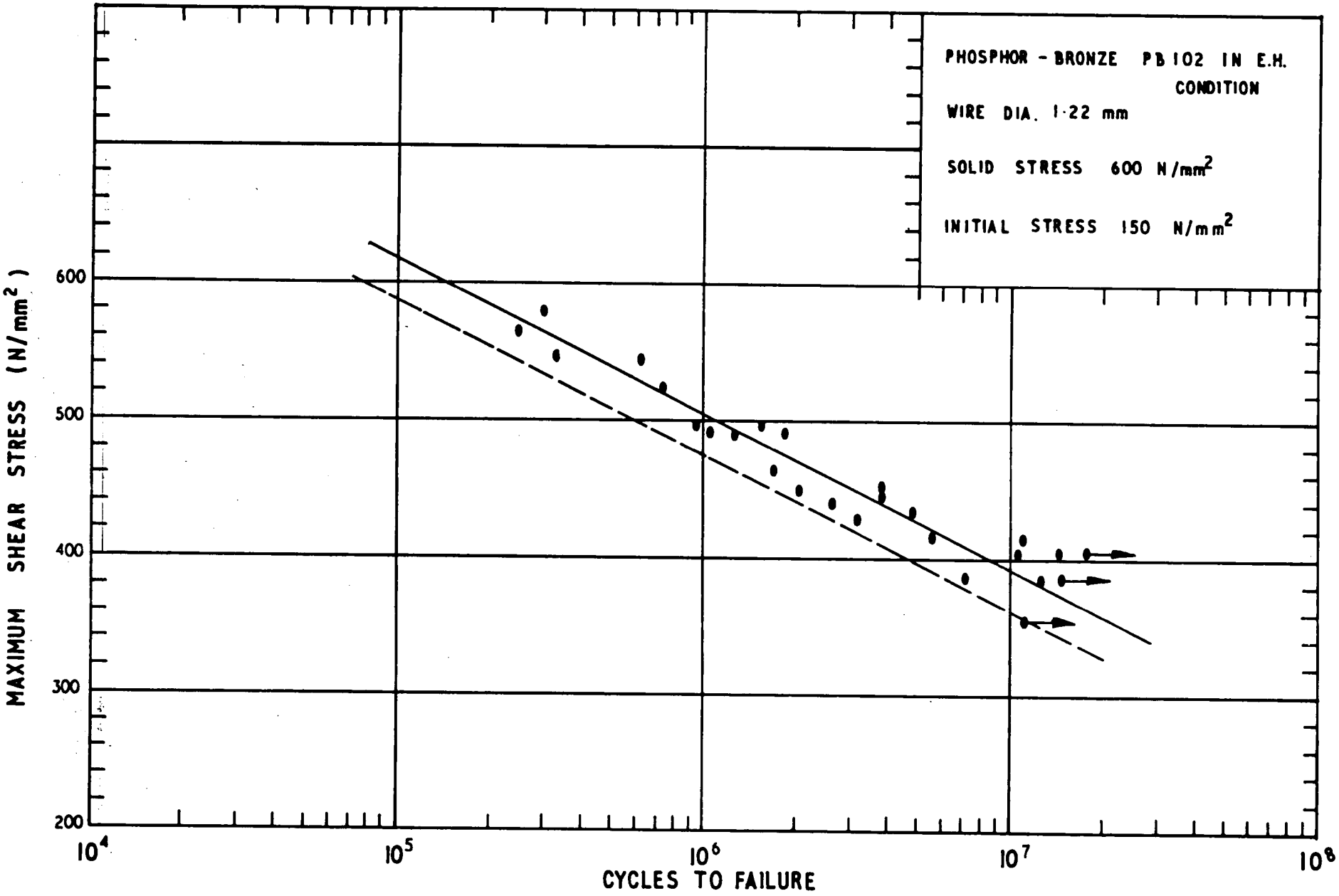

FIG. 2 TORSIONAL S/N CURVE FOR PHOSPHOR - BRONZE SPRINGS. INITIAL STRESS 150 N/mm²

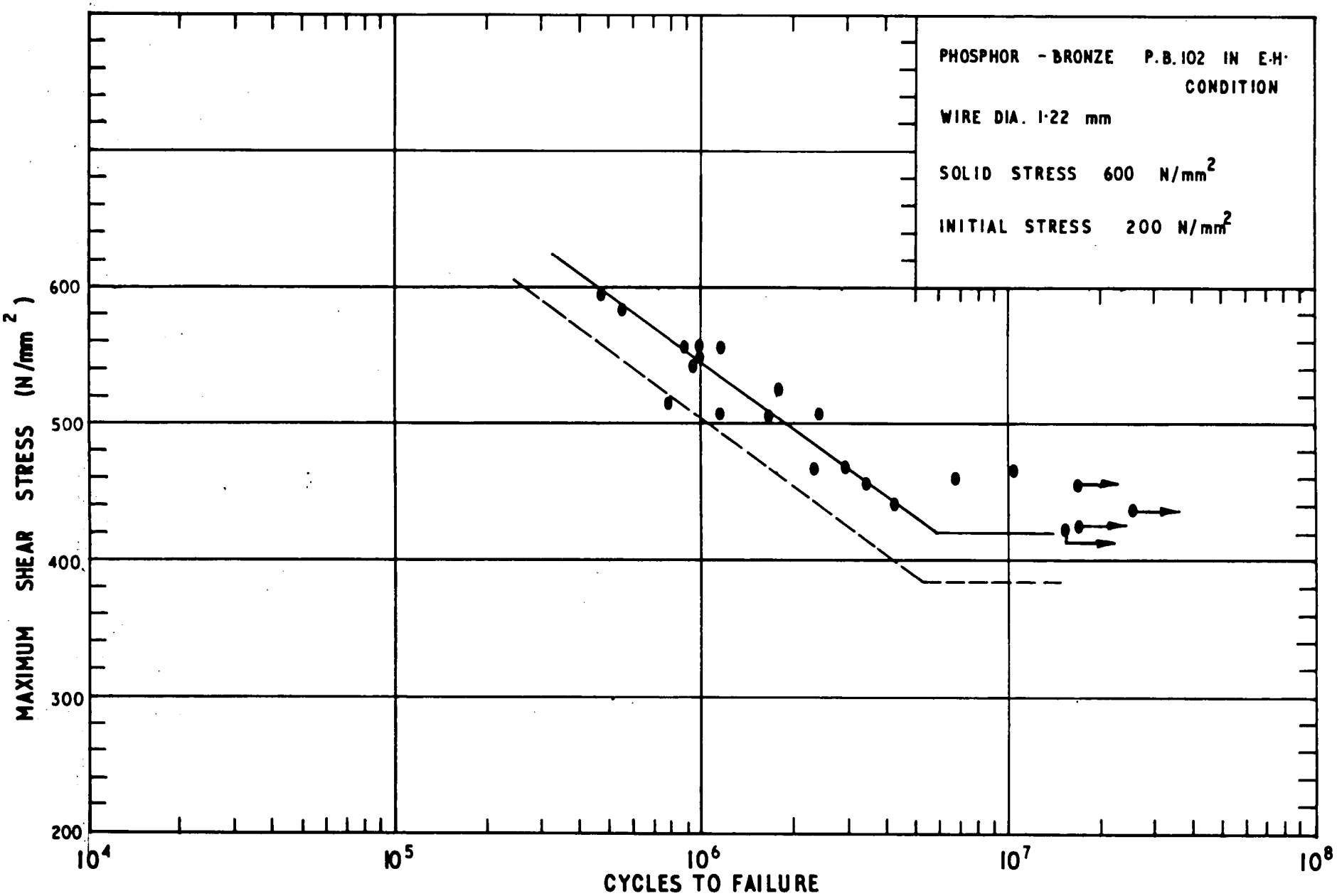

FIG. 3 TORSIONAL S/N CURVE FOR PHOSPHOR - BRONZE SPRINGS. INITIAL STRESS 200 N/mm²

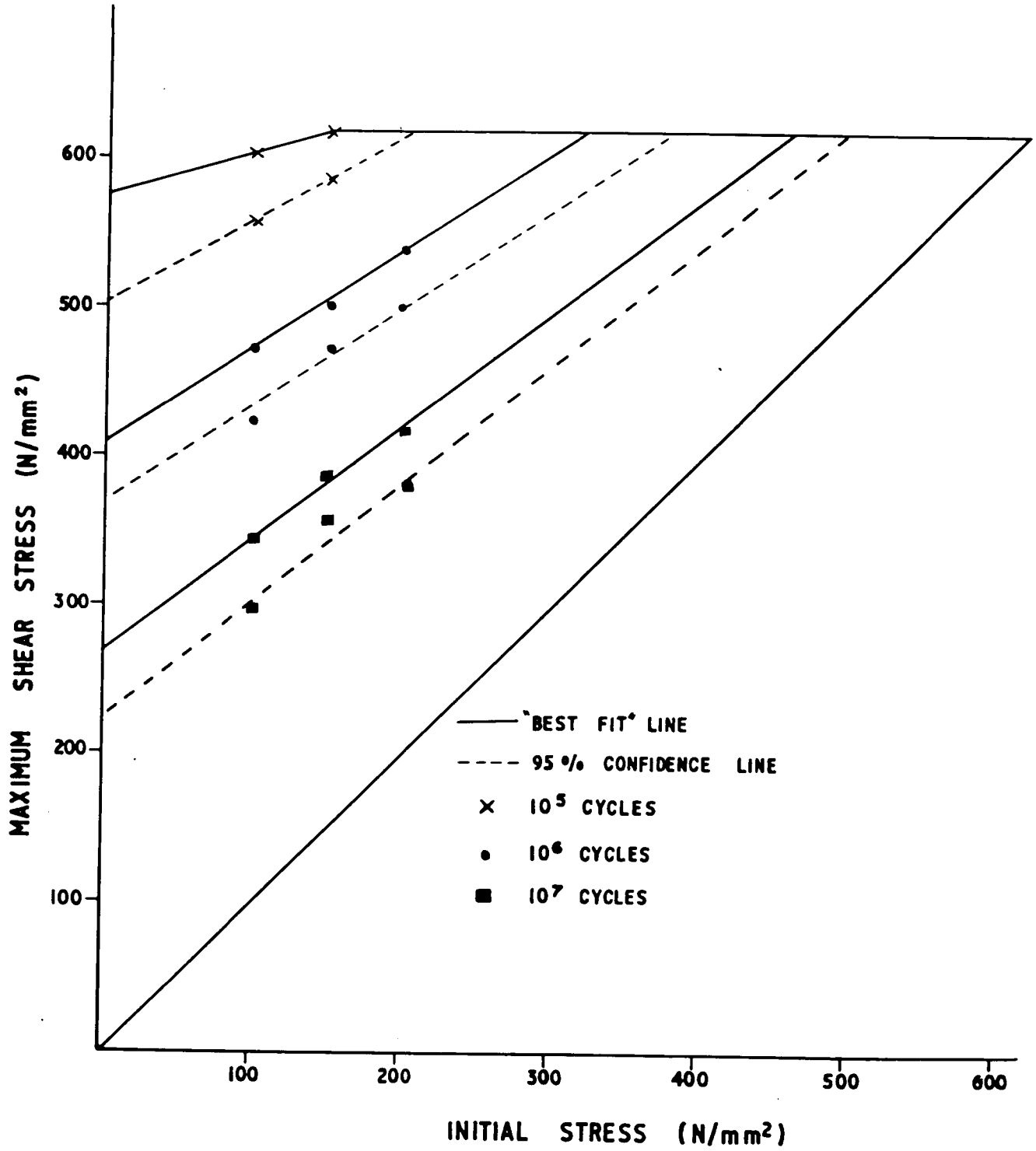

FIG. 4. MODIFIED GOODMAN DIAGRAM FOR PHOSPHOR-BRONZE SPRINGS.

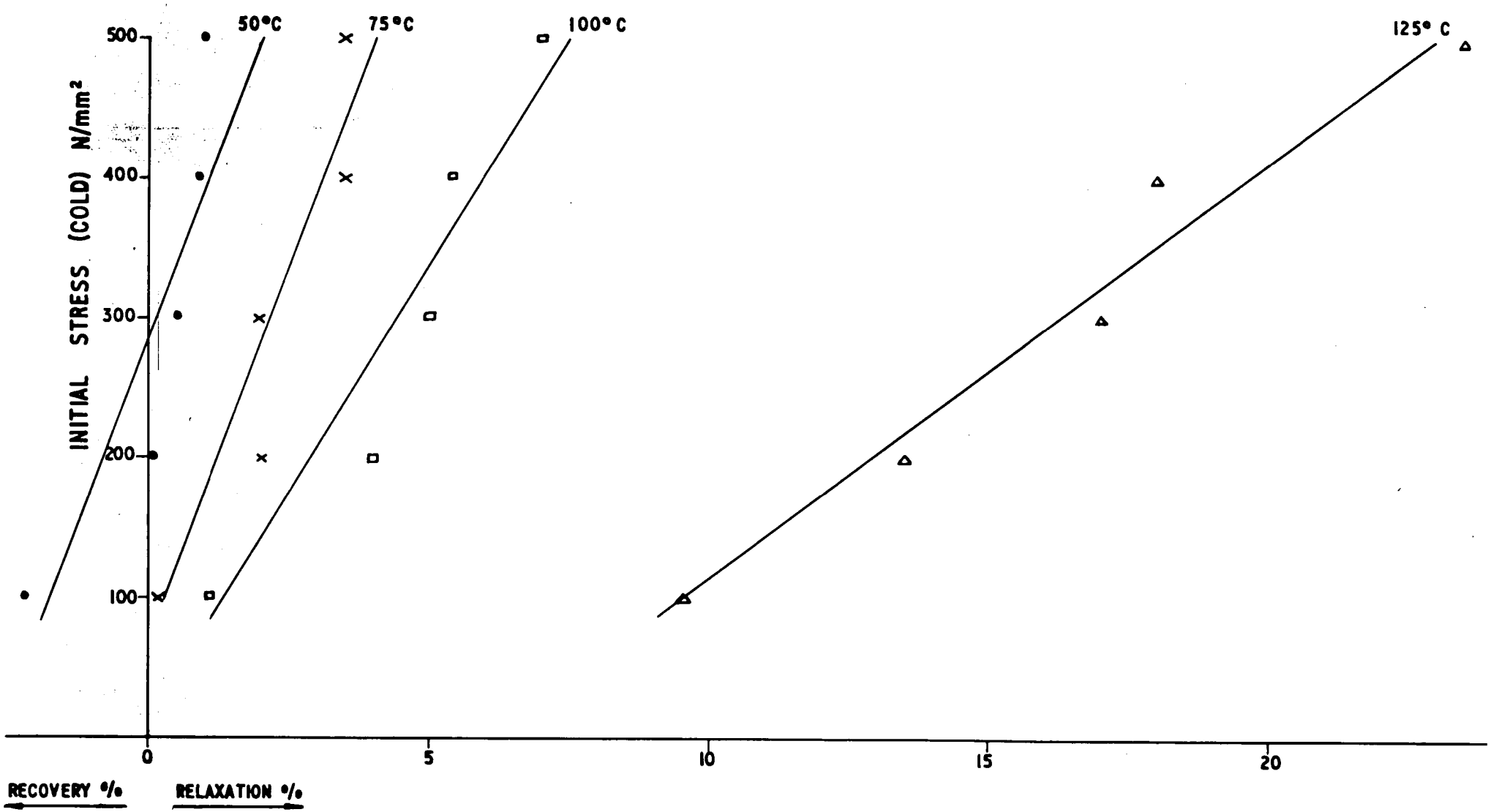

FIG. 5 RELAXATION CURVES FOR PHOSPHOR - BRONZE SPRINGS (72 HR. TEST DURATION)

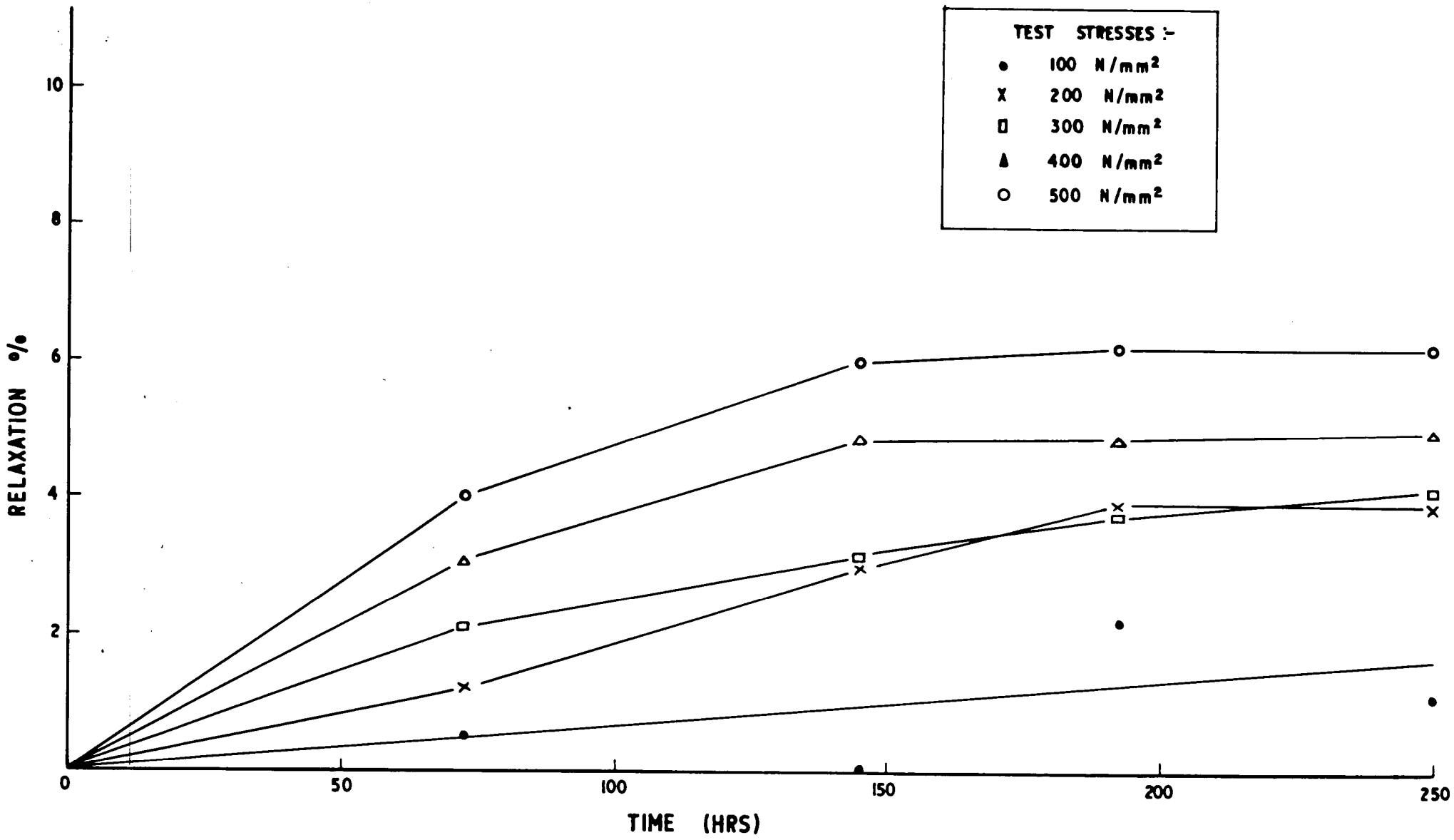

FIG. 6 RELAXATION —TIME CURVES FOR PHOSPHOR - BRONZE SPRINGS (AT 75°C)