THE SPRING RESEARCH AND MANUFACTURERS' ASSOCIATION

THE FATIGUE AND RELAXATION RESISTANCE OF COPPER-BERYLLIUM HELICAL COMPRESSION SPRINGS

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G. B. Graves, A.Met., M.I.M.

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SUMMARY

The tensile and torsional properties of two qualities of Cu-Be wire have been investigated. Fatigue tests carried out on springs produced from the two qualities have shown that springs made from hard drawn wire and aged after coiling are superior, in terms of dynamic properties, to 'pre-hardened wire springs.

Elevated temperature relaxation tests of 72 hours' duration carried out at various initial stress levels and temperatures up to 150°C have also demonstrated the better properties of springs manufactured from hard drawn wire and subsequently aged. Long term tests to 1000 hours have been undertaken for limited stresses and temperatures to illustrate the effects of time at temperature upon the resulting loss in load.

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1. INTRODUCTION

Non-ferrous spring materials constitute a relatively small proportion of the total volume of materials used for the manufacture of springs; nevertheless non-ferrous materials, particularly copper-beryllium alloys, play a vital role in the light spring industry in meeting certain service requirements not readily met by other ferrous or non-ferrous materials.

Copper-beryllium alloys, containing approximately 1.8% Be, are one of the most attractive non-ferrous materials from the spring designer's point of view because of the combination of good mechanical properties, electrical and thermal conductivity, and resistance to wear and corrosion.

In the present report, the data on both static and dynamic properties, as well as relaxation behaviour, are given for springs produced from hard drawn wire and pre-tempered wire.

2. MATERIAL

2.1 Composition

Two batches of copper-beryllium wire, manufactured in accordance with BS 2873:1969, were obtained. The actual chemical compositions are given in Table I, together with the nominal composition specified for material designated CB101.

2.2 Wire

One consignment of 1.22 mm diameter wire was supplied in the hard drawn condition, which, after spring coiling, required ageing. The second batch of 1.22 mm diameter wire was purchased in the 'pre-tempered' condition; 'pre-tempering' being an ageing process undertaken by the wire manufacturer to strengthen the material prior to spring coiling.

2.3 Springs

Springs were manufactured from each of the two batches of wire according to the designs given in Table II. Stress calculations were based on 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

The hard drawn wire was successfully coiled using a Torrington 115A machine. Springs were subsequently aged at 335°C for 2 hours A.C. prior to end grinding. After grinding, all springs were prestressed to solid until stable to give the free lengths quoted in Table II. Difficulty was experienced when attempting to coil springs automatically from 'pre-tempered' wire; no matter what adjustments were made to the machine, a satisfactory spring could not be produced. It was therefore necessary to resort to hand coiling using a Carlson machine. Because of the lower tensile strength, the solid stress was reduced to give the same solid stress/ U.T.S. ratio.

After being coiled, the springs were stress relieved at 230°C for 20 minutes A.C., in keeping with the wire manufacturer's recommendations for Cu-Be wire which has been pre-hardened by ageing. End grinding and prestressing followed to produce springs according to Table II.

3. EXPERIMENTAL PROCEDURE

3.1 Tests on Wire

Tensile tests were undertaken on both qualities of wire, both in the 'as received' condition amd also after heat treatment, the hard drawn material being aged at 335°C for 2 hours A.C. and the 'pre-tempered' wire being stress relieved at 230°C for 20 minutes.

Testing was carried out on an Amsler multi-range machine, equipped with a load-extension autographic recorder, using an extensometer having a gauge length of 250 mm. The results obtained are shown in Table III, these data being average figures of duplicate tests. Torsional stress-strain determinations were also carried out on wire in each of the four metallurgical conditions. A gauge length of one hundred times the wire diameter was employed and all stresses calculated on the formula based on the elastic theory, viz:

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

where: q = shear stress
T = torque
d = wire diameter

The results obtained on duplicate tests were averaged and are given in Table IV.

3.2 Fatigue Tests

The two batches of springs in the aged and stress relieved conditions respectively were initially load tested to determine the various compressed lengths necessary for setting up the forced-motion fatigue testing machine. Each batch was fatigue tested at two initial stress levels and, by varying the maximum stress on the springs, the endurance could be recorded for selected stress levels. From these data, S-N curves (Figs. 1 and 2) were drawn and modified Goodman diagrams constructed (Figs. 3 and 4). All testing was carried out at a speed of 25 Hz.

3.3 Relaxation Tests

Much data have been produced in the past based on a test duration of 72 hours; to enable comparisons to be made with other spring materials, the same test duration was employed for part of this investigation. Five test stresses, between 200 and 600 N/mm^2, and four test temperatures were selected. For each combination of stress and temperature, tests were carried out in triplicate. Each spring was load tested to determine the compression necessary to achieve the selected stress, before it was mounted on a nut and bolt assembly. The springs were then subjected to the appropriate test temperature for 72 hours, after which they were allowed to cool, were dismantled and load tested again to their original compressed length. From the results of the load tests before and after the springs had been subjected to temperature, the percentage relaxation could be calculated.

The results of the 72 hour relaxation tests can be seen in Figs. 5 and 6.

A second series of relaxation tests was carried out for the purpose of relating the relaxation behaviour to the duration of test at two elevated temperatures. Based on the data obtained from the earlier work, two initial stress levels were used and the relaxation behaviour of both qualities of Cu-Be springs were monitored up to 1000 hours. These data are shown in Figs. 7 to 9.

4. DISCUSSION

4.1 Wire Properties

Ageing the hard drawn Cu-Be wire had a marked effect on the tensile strength and proof stress properties. The tensile strength was raised from 890 N/mm^2 to 1410 N/mm^2 and the limit of proportionality, 0.05% and 0.1% proof stress values also increased. It is of interest to note that the limit of proportionality and proof stress values bore a similar proportional relationship to the appropriate tensile strengths for both the hard drawn, and the hard drawn and aged* wire.

The 'pre-tempered' wire possessed a higher tensile strength than the hard drawn material, as was to be expected since ageing had been undertaken by the wire manufacturer. The limit of proportionality and proof stress values, on the other hand, were not much higher than those of hard drawn wire and were certainly inferior to the figures for hard drawn and aged material.

Stress relieving the 'pre-tempered' wire did improve the tensile strength somewhat but a more marked improvement was noticed in the limit of proportionality and proof stress properties. After stress relief, these values were again a similar proportion of the tensile strengths. It was rather surprising to find the 'pre-tempered' wire responding to a stress relief heat treatment (230°C for 20 minutes) in this manner, in view of the fact that it had already received an ageing treatment at a much higher temperature. Possible explanations for this finding are that, before tensile testing, it was necessary to straighten the 'pre-tempered' wire and the additional cold work may have depressed the elastic properties artificially. Alternatively, after 'pre-tempering', the wire may have received a slight amount of further drawing which would also depress the elastic properties; on subsequent low temperature heat treatment these properties would recover.

The torsional properties of the Cu-Be wires under investigation are presented in Table IV.

Ageing the hard drawn material produced a considerable increase in the maximum shear strength but hardly any improvement in the 0.05% or 0.1% proof stress values. At higher proof stresses, i.e. 0.2% amd 0.5%, there is a perceptible difference between the hard drawn and hard drawn aged wire; this is presumably a reflection of the difference in their respective maximum torsional strengths.

Again the 'pre-tempered' wire exhibited a higher maximum strength than the hard drawn wire but the elastic-plastic properties, as shown by the proof stress values, were similar. Stress relieving the 'pre-tempered' material had little effect on its maximum strength, unlike the behaviour experienced in the tensile test. The torsional proof stress properties did improve as a result of the stress relief heat treatment and became very similar to those obtained for the hard drawn aged material, even though there was a difference in the respective maximum strength values.

4.2 Fatigue Properties

The fatigue data obtained on springs manufactured from the two qualities of wire are shown in Figs. 1 and 2. The full lines describing the limited life experimental data were established by the least squares method and the 95% confidence limits are shown by dotted lines. Goodman diagrams showing the influence of the initial stress on the spring to the maximum stress for various endurance levels are given for mean life data in Fig. 3 and for 95% confidence in Fig. 4.

It is clear that at 10^7 cycles' endurance, springs made from hard drawn wire possess the better resistance to fatigue. At 10^5 and 10^6 cycles there is little difference between the two qualities.

Reference to Table V allows comparisons to be made between these data and those obtained for phosphor-bronze springs$^{(1)}$. At zero initial stress, the fatigue strength at 10^7 cycles is 290 N/mm^2 for hard drawn and aged springs and 220 N/mm^2 for springs made from 'pre-tempered' wire, compared with 270 N/mm^2 for phosphor-bronze, even though the latter material had the much lower tensile strength of 860 N/mm^2.

At initial stresses of 100 and 200 N/mm^2, the fatigue behaviour at 10^7 cycles followed a similar pattern, with the Cu-Be hard drawn and aged springs exhibiting somewhat better strength properties than phosphor-bronze which, in turn, were better than those of springs produced from 'pre-tempered' wire.

In general terms, it can be concluded that the use of a much higher strength Cu-Be alloy does not result in a corresponding increase in fatigue resistance when compared with a phosphor-bronze wire of lower tensile strength.

4.3 Relaxation Properties

Curves have been constructed relating initial stress in Cu-Be springs to the resulting relaxation after 72 hours at various temperature levels (Figs. 5 and 6). These follow the usual pattern of behaviour, in that increasing the stress level and/or temperature, causes an increase in relaxation. The most significant feature is the considerable difference between the two qualities, springs made from the hard drawn wire having much the better resistance to relaxation by a factor of about three. It is clear that hard drawn and aged Cu-Be springs could be employed at stresses up to 600 N/mm^2

and at temperatures up to 125°C without experiencing undue loss in load bearing capacity. Springs made from 'pre-tempered' wire, on the other hand, would certainly show excessive relaxation under similar test conditions and if such springs were used, the limiting operating temperature would be 75°C at stress levels less than about 400 N/mm^2.

Relaxation data for phosphor-bronze springs have been reported previously by SRAMA(1) and comparisons show that the hard drawn and aged Cu-Be springs exhibit superior relaxation resistance. Springs manufactured from 'pre-tempered' wire, however, had similar relaxation properties to phosphor-bronze springs and only at test temperatures of 125°C and above did the present 'pre-tempered' Cu-Be springs have superior resistance.

Taking into consideration the fatigue and relaxation behaviour of 'pre-tempered' Cu-Be and phosphor-bronze springs, there would appear to be little advantage in using the former, more expensive material unless the static and dynamic stress levels employed were in excess of those that could be satisfactorily accommodated by the lower strength phosphor-bronze material.

Although it is convenient to measure and compare relaxation behaviour after some particular test duration such as 72 hours, many operating conditions in service are in excess of this figure. Consequently, some knowledge of the performance of springs at longer test durations is desirable. The relaxation of Cu-Be springs has been monitored up to 1000 hours and the results are illustrated in Figs. 7 to 9. Testing hard drawn and aged springs at 100°C for times up to 1000 hours at stresses of 300 and 500 N/mm^2 demonstrated their suitability for long term operation with a maximum load loss of about 4%. Increasing the test temperatures (Fig, 8) to 150°C caused relaxation to occur at an increasing rate, so that, after

1000 hours, approximately 16% relaxation had taken place which may or may not be acceptable, depending on the service application.

Long term tests on springs made from 'pre-tempered' Cu-Be wire (Fig. 9) again demonstrated the inferior relaxation behaviour of this material compared with the hard drawn and aged quality. In this case the influence of initial stress on the springs also appeared to be greater. In view of the large amount of relaxation experienced after 1000 hours at 100°C, testing was limited to one temperature.

5. CONCLUSIONS

1. Ageing hard drawn wire and stress relieving 'pre-tempered' Cu-Be wire effect a considerable increase in the tensile properties.

2. The fatigue properties of springs made from hard drawn wire subsequently aged after coiling were superior to those for 'pre-tempered' Cu-Be springs only at 10^7 cycles.

3. The fatigue limit of'pre-tempered' Cu-Be springs at zero initial stress was not as high as that of phosphor-bronze springs.

4. At higher initial stress and relatively low endurance levels, the 'pre-tempered' Cu-Be springs were slightly better than the phosphor-bronze springs.

5. Springs made from hard drawn and aged Cu-Be wire exhibited greatly superior relaxation resistance compared with springs made from either 'pre-tempered' Cu-Be or phosphor-bronze wire.

6. A maximum operating temperature for hard drawn and aged springs would be about 125°C and for 'pre-tempered' Cu-Be springs about 75°C, depending on stress and tolerable relaxation.

7. Hard drawn and aged springs operating at 100°C with initial stress levels up to 500 N/mm^2 exhibited only 4% relaxation even after 1000 hours' duration. At 150°C, however, relaxation of the order of 16% occurred.

6. REFERENCE

1. HEYES, P. F. "The Fatigue and Relaxation Properties of Helical Compression Springs made from Phosphor-Bronze Wire". SRAMA Report No. 243.

TABLE I CHEMICAL COMPOSITION

	% Cu	% Ni + Co	% Be	% Res.
Specified	Rem.	0.05 - 0.40	1.7 - 1.9	0.50 max.
Hard Drawn	97.50	0.24	1.77	0.49
Pre-tempered	97.52	0.29	1.72	0.47

TABLE II SPRING DESIGNS

	Hard Drawn	Pre-Tempered
Wire Diameter (mm)	1.22	1.22
Mean Coil Diameter (mm)	8.18	8.81
Total Coils	8	8
Active Coils	6	6
Free length (after grinding and prestressing) (mm)	30.02	30.45
Solid Stress (N/mm^2)	980	850

TABLE III TENSILE PROPERTIES OF COPPER - BERYLLIUM 1.22 mm WIRE

Condition	Tensile Strength		Limit of Proportionality		0.05% Proof Stress		0.1% Proof Stress		Reduction of Area	Elongation on 25 mm
	N/mm^2	$tonf/in^2$	N/mm^2	$tonf/in^2$	N/mm^2	$tonf/in^2$	N/mm^2	$tonf/in^2$	%	%
Hard Drawn	890	57.6	540	34.9	715	46.2	805	52.1	63.5	1.6
Hard Drawn Aged	1410	91.4	900	58.3	1140	73.8	1225	79.3	30.6	1.6
Pre-tempered	1145	74.1	580	37.6	765	49.6	880	57.0	46.5	3.1
Pre-tempered and stress relieved	1255	81.2	795	51.4	1005	65.2	1120	72.6	38.6	-

TABLE IV TORSIONAL PROPERTIES OF COPPER - BERYLLIUM 1.22 mm WIRE

Condition	Max. Torsional Strength		0.05% Proof Stress		0.1% Proof Stress		0.2% Proof Stress		0.5% Proof Stress	
	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
Hard Drawn	635	41.1	355	22.9	410	26.5	470	30.5	550	35.7
Hard Drawn Aged	905	58.6	360	23.4	430	27.8	550	35.6	705	45.7
Pre-tempered	755	48.8	320	20.6	355	23.0	415	26.8	560	36.1
Pre-tempered and stress relieved	760	49.3	380	24.7	445	28.8	545	35.2	655	42.3

TABLE V FATIGUE RATIOS

Material	Tensile Strength N/mm^2	Fatigue Strength N/mm^2 and Fatiuge Ratios at:-								
		Zero initial			100 N/mm^2			200 N/mm^2		
		10^5	10^6	10^7	10^5	10^6	10^7	10^5	10^6	10^7
Ph - Bronze	860	575 .67	410 .48	270 .31	600 .70	470 .55	345 .40	-	540 .63	420 .49
Cu-Be hard drawn aged	1410	600 .43	380 .27	290 .21	680 .48	450 .32	370 .26	750 .53	530 .38	450 .32
Cu-Be Pre-tempered & stress relieved	1255	600 .48	410 .33	220 .18	660 .53	480 .38	290 .23	730 .58	550 .44	365 .29

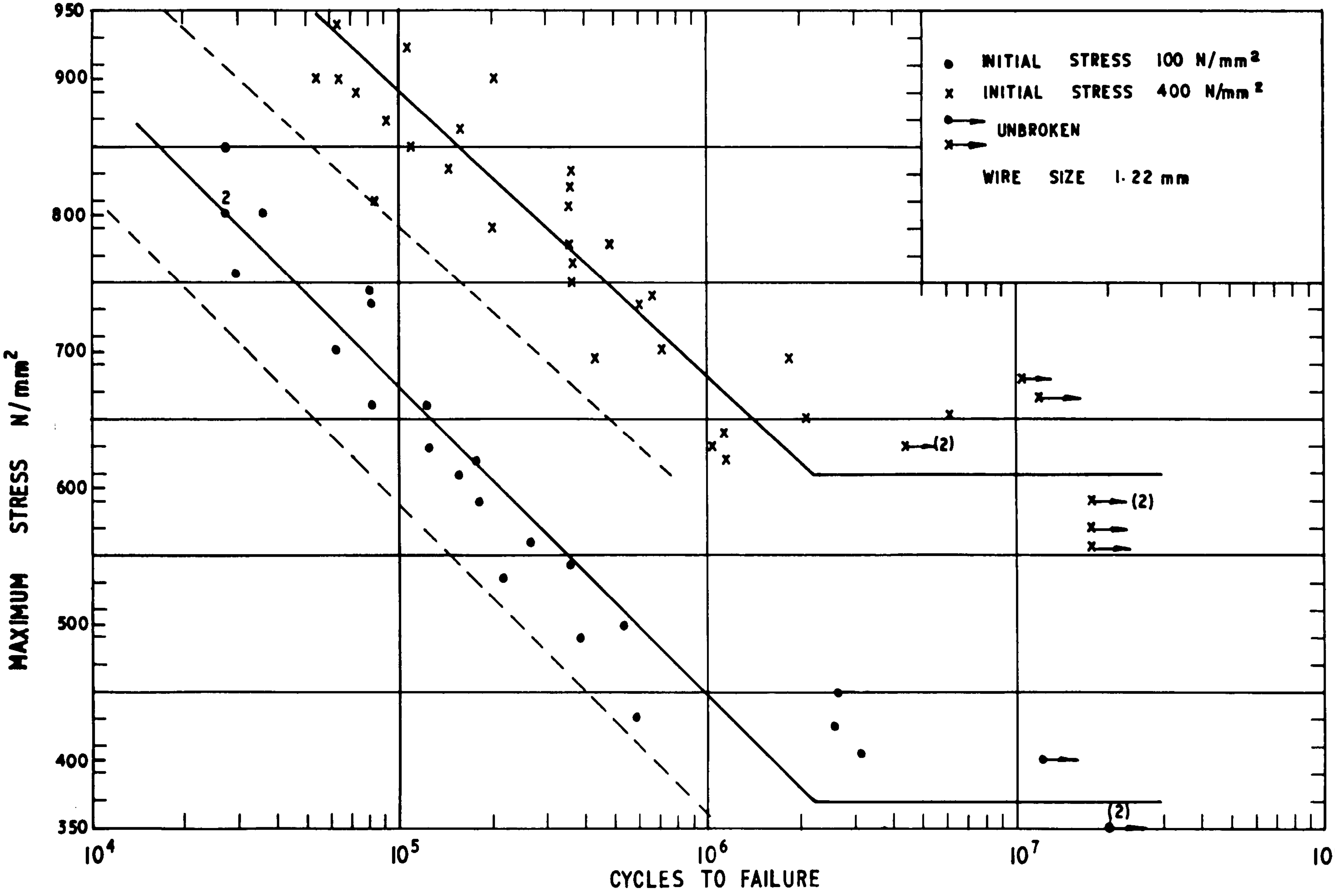

FIG. 1. S-N CURVES FOR Cu-Be SPRINGS MADE FROM HARD DRAWN AND AGED WIRE.

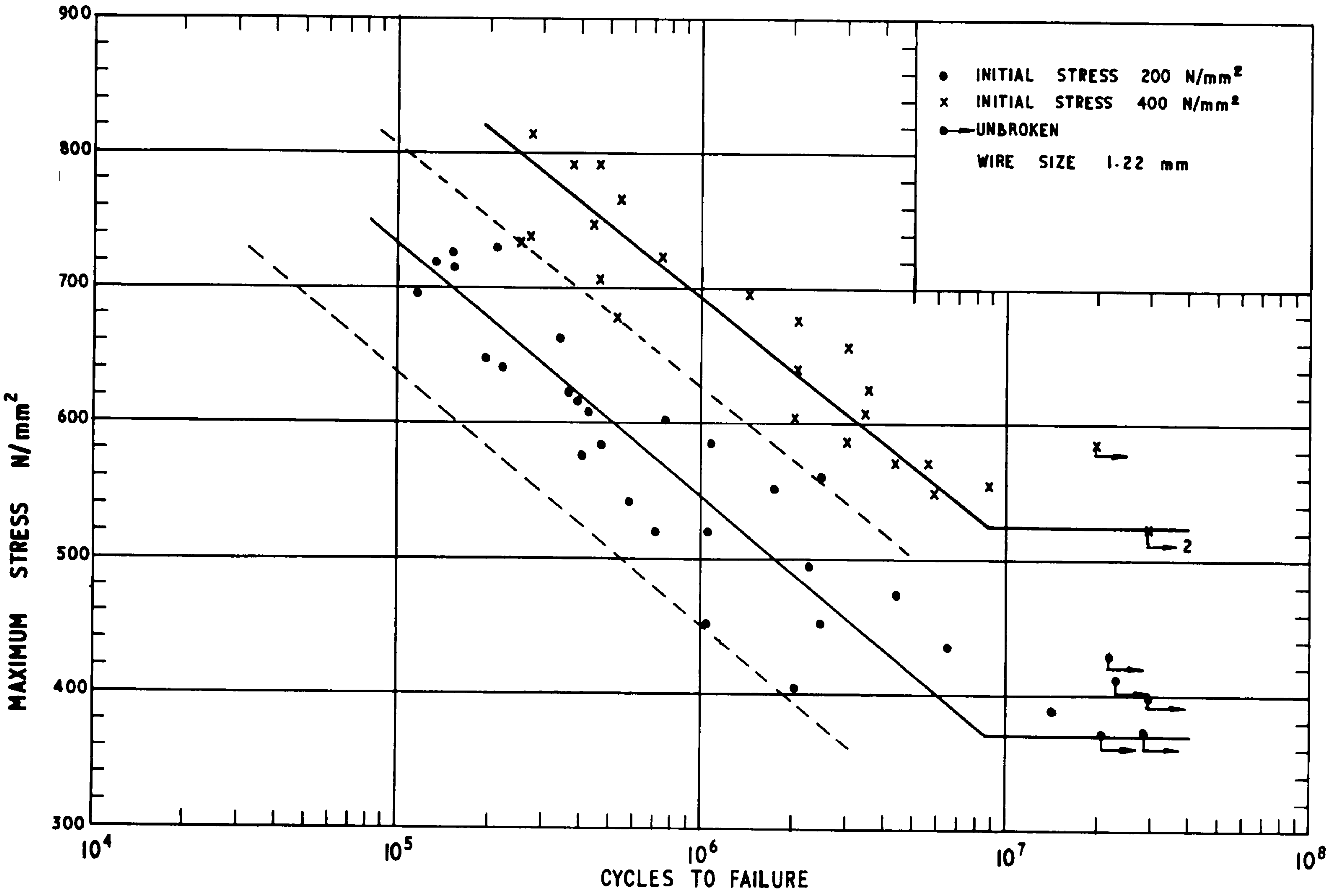

FIG. 2 S-N CURVES FOR Cu-Be SPRINGS MADE FROM 'PRE-TEMPERED' WIRE.

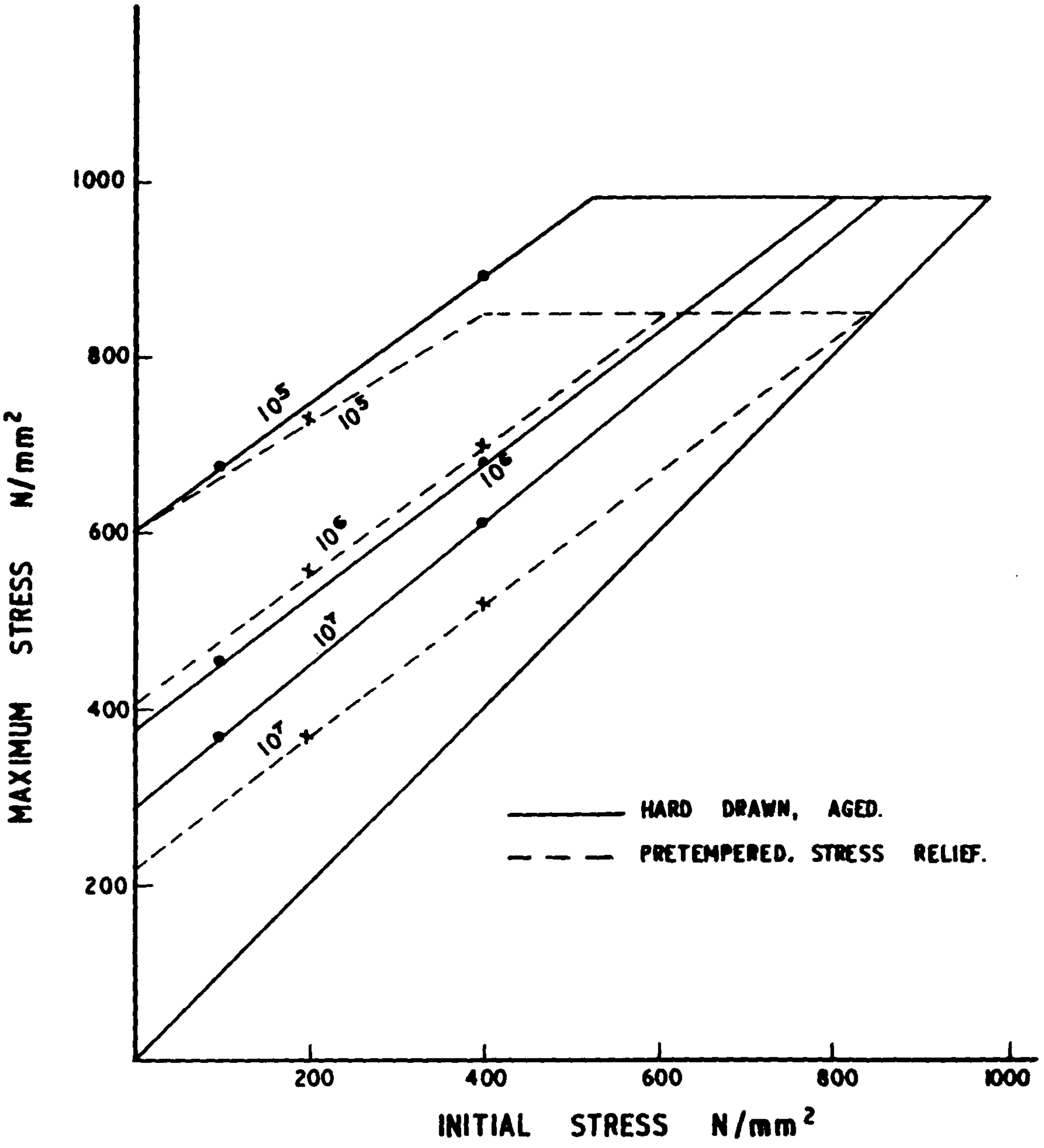

FIG. 3 MODIFIED GOODMAN DIAGRAM FOR Cu-Be SPRINGS.

(MEAN - LIFE DATA, NOT TO BE USED FOR DESIGN PURPOSES)

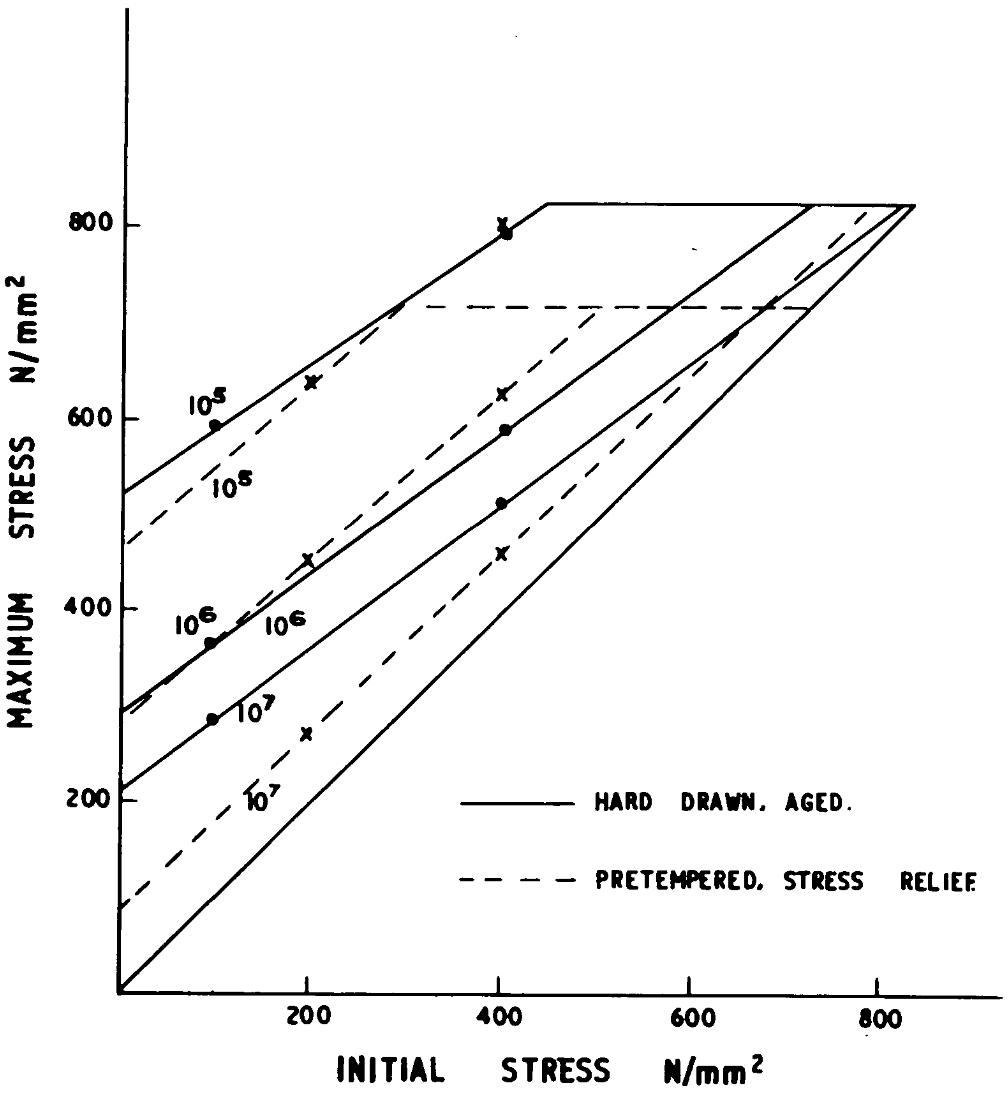

FIG. 4 MODIFIED GOODMAN DIAGRAM FOR Cu-Be SPRINGS BASED ON 95% CONFIDENCE LEVELS.

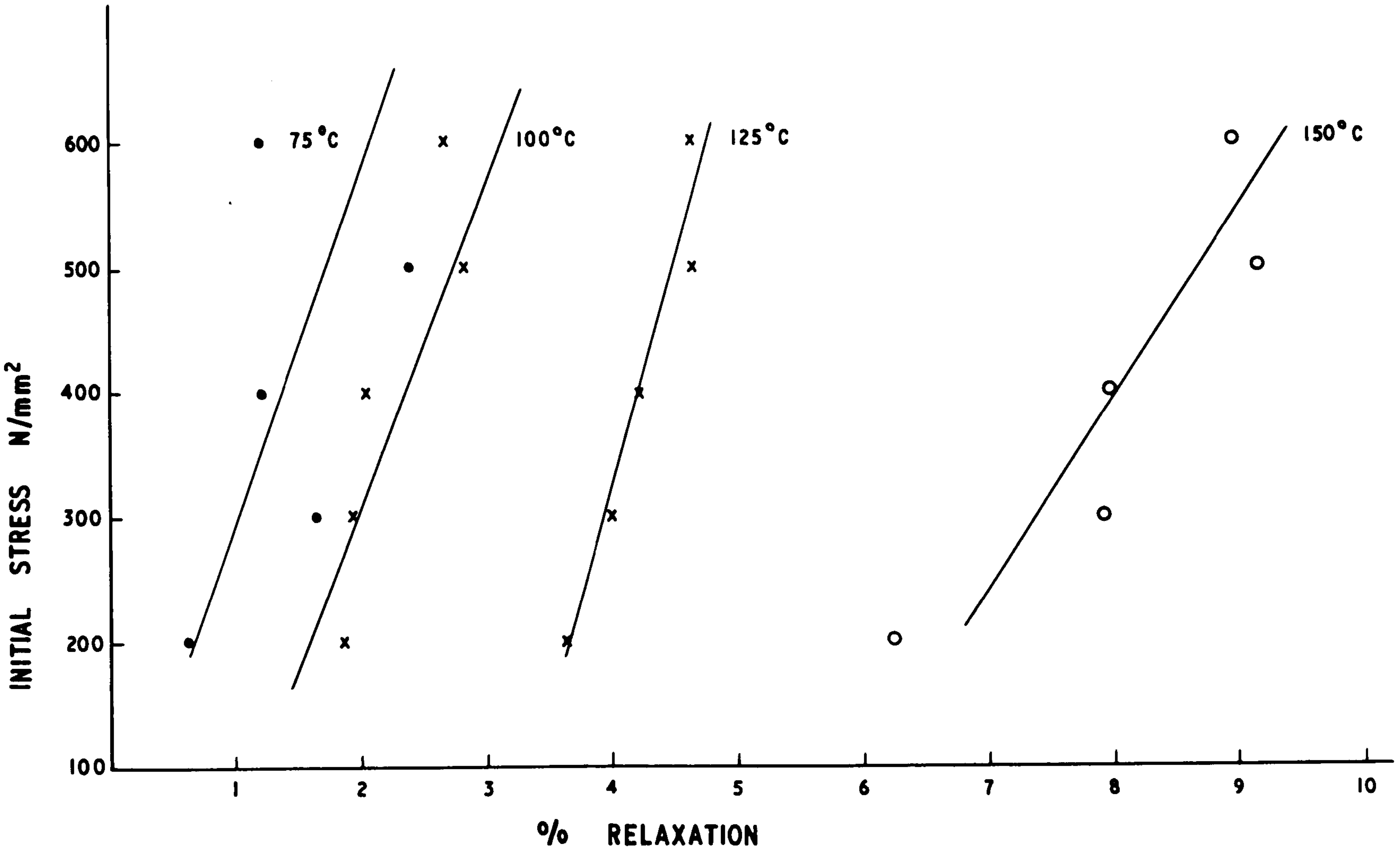

FIG. 5 RELAXATION CURVES FOR HARD DRAWN AND AGED Cu-Be WIRE SPRINGS.
(TEST DURATION 72 h)

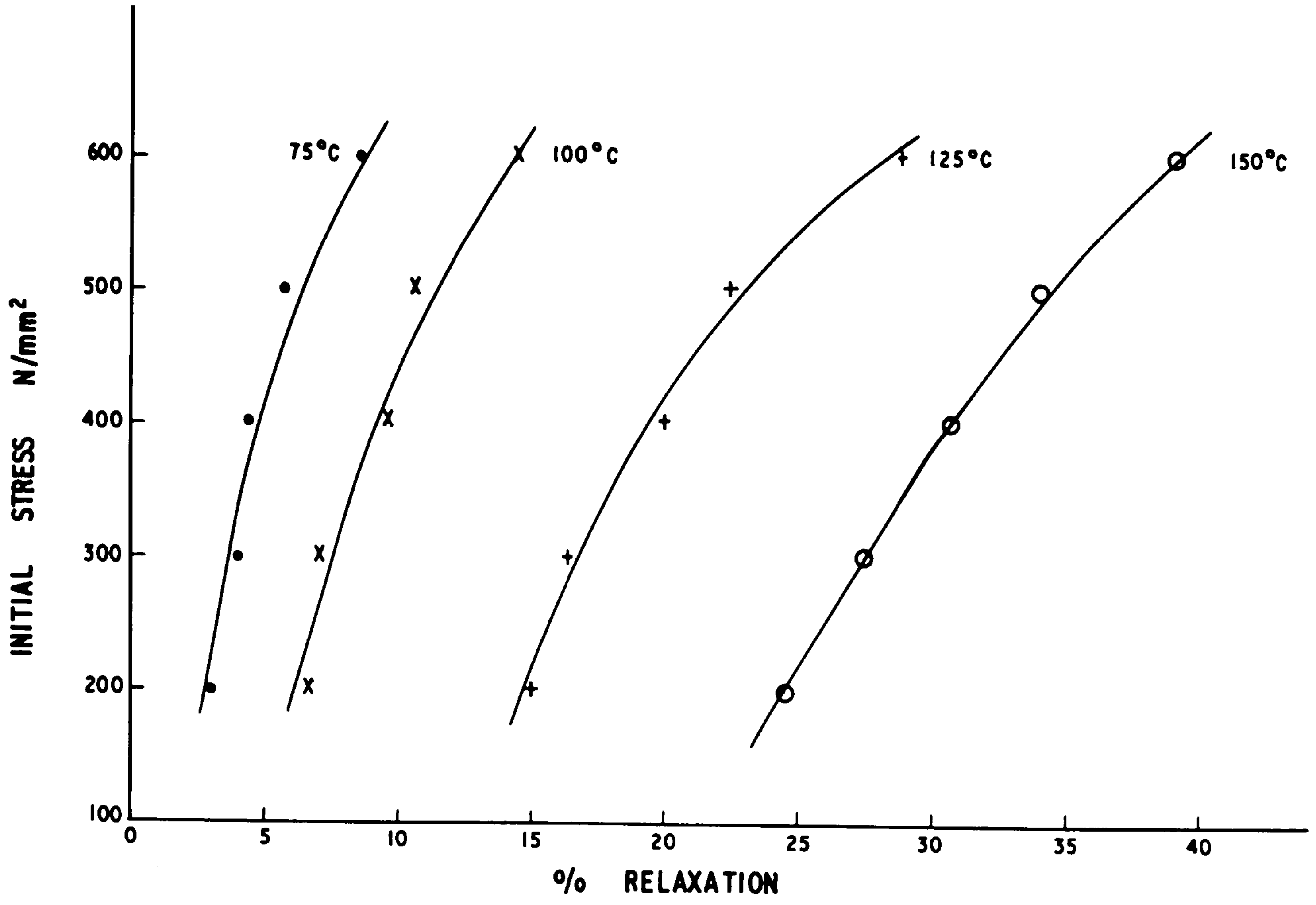

FIG. 6 RELAXATION CURVES FOR 'PRETEMPERED' Cu-Be WIRE SPRINGS.
(TEST DURATION 72 h)

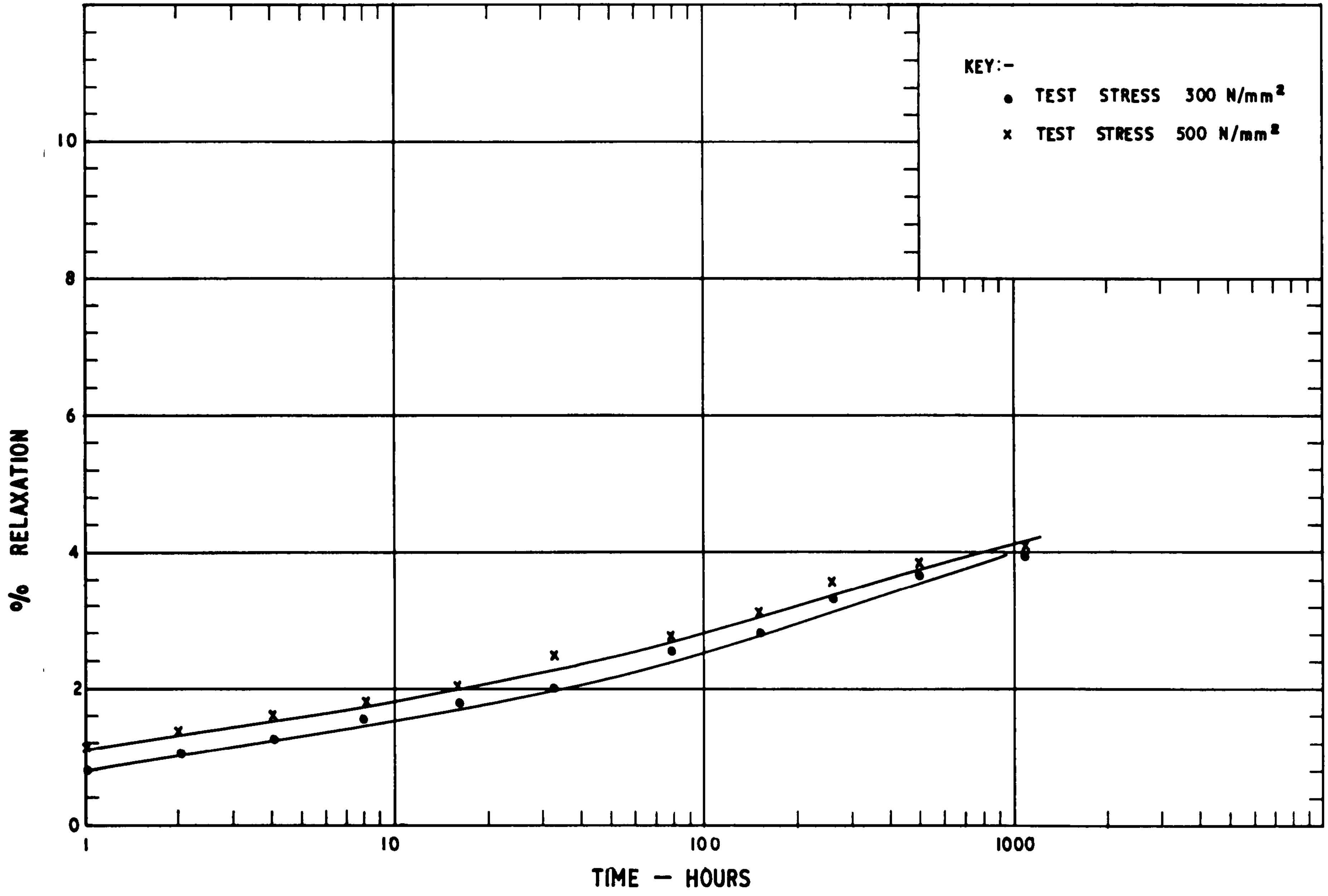

FIG. 7 RELATIONSHIP BETWEEN RELAXATION AND TIME FOR HARD DRAWN Cu-Be WIRE SPRINGS (TEST TEMP. 100°C.)

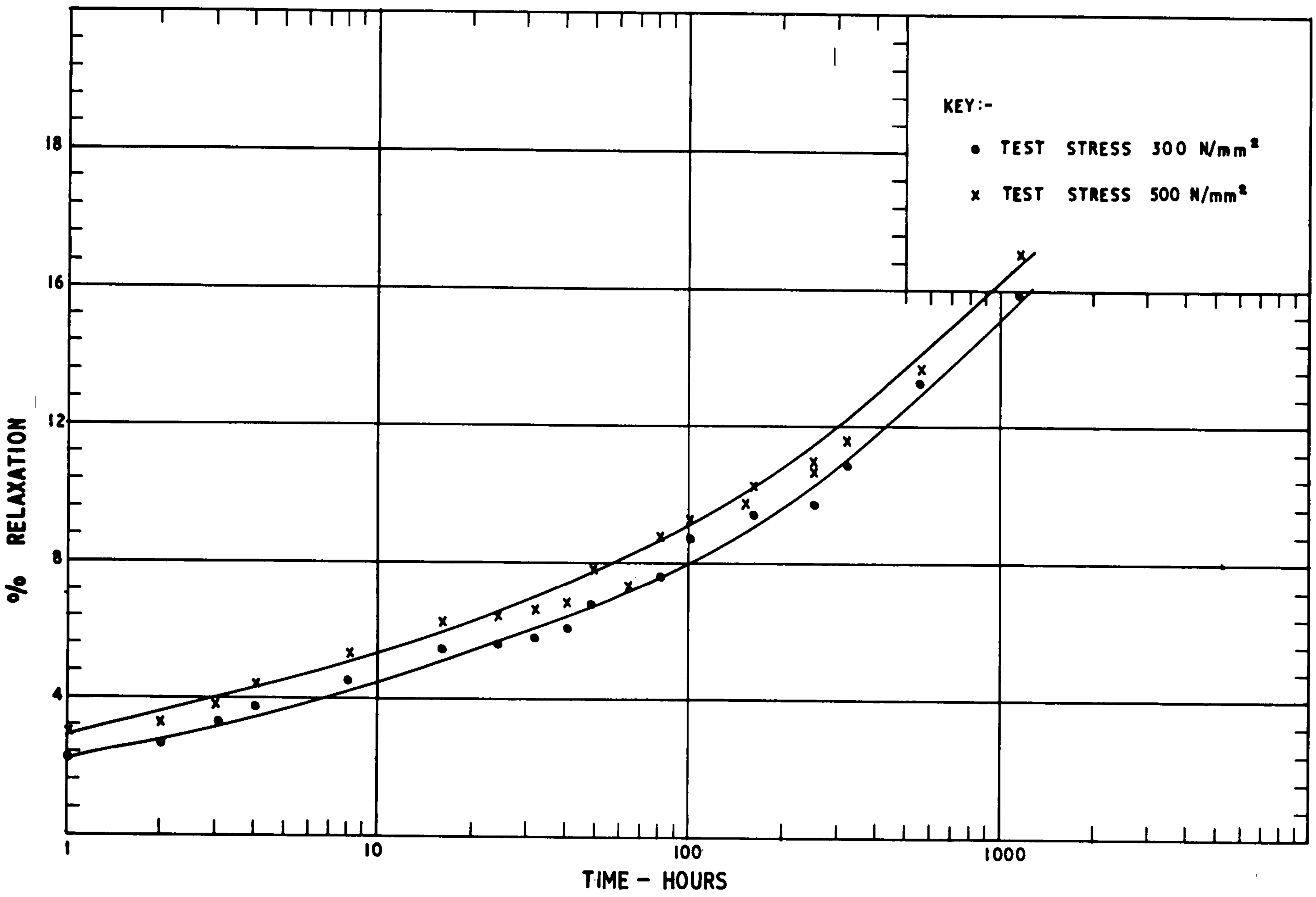

FIG. 8 RELATIONSHIP BETWEEN RELAXATION AND TIME FOR HARD DRAWN Cu-Be WIRE SPRINGS. (TEST TEMP. 150°C)

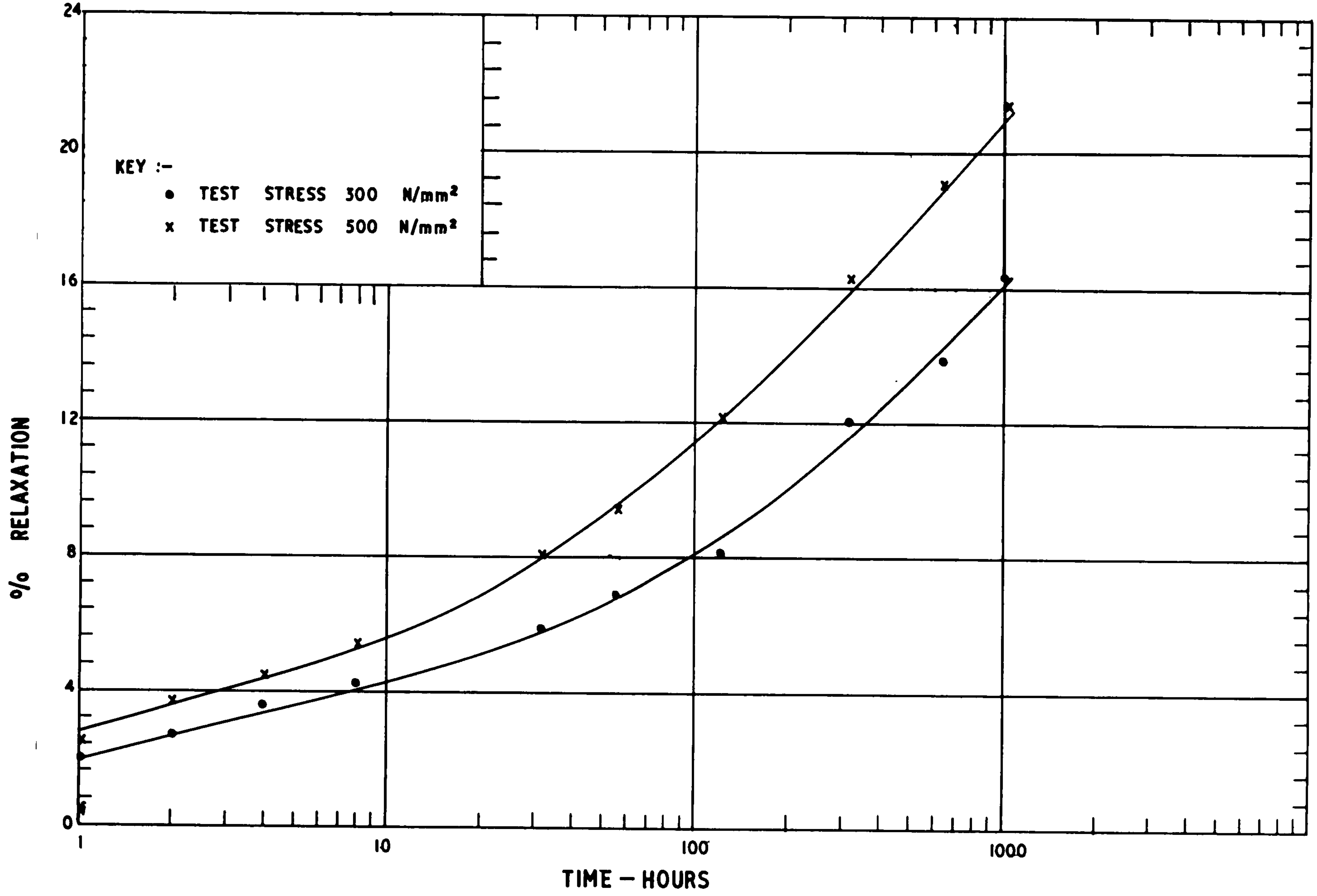

FIG. 9 RELATIONSHIP BETWEEN RELAXATION AND TIME FOR 'PRETEMPERED' Cu-Be WIRE SPRINGS (TEST TEMP. 100°C)